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COVER PHOTOGRAPH

Mt. Goddard in the Sierra Range of California. This peak separates the Kings and San Joaquin River Watersheds. The area is well suited for cloud physics research and weather modification operations.

WEATHER MODIFICATION ASSOCIATION

P.O. Box 125
Altadena, California
91001

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A CALL FOR ACTION

by

Vincent J. Schaefer, Director
State University of New York,
Albany, New York

What are we waiting for?

About seventeen years ago in Part I of the Final Report of Project Cirrus, (1), I summarized the conclusions and recommendations our group had reached after seven years of an intensive effort in laboratory field and flight research in cloud physics and weather modification. This report was prepared at the conclusion of 225 flight operations carried out under Project Cirrus. Since this final report had a somewhat limited circulation (300 copies) it may be of interest at this time to cite the summary and recommendations contained at the end of my 170 page report.

"On the basis of the laboratory, field, and flight studies conducted during the five-year period of active research under the Project Cirrus program, the following conclusions seem to be justified.

1. Supercooled clouds may be effectively modified by dry ice and/or silver iodide seeding.

2. Nuclei are of primary importance in the initial stages of the development of precipitation. The concentration of effective condensation and/or ice nuclei, together with the liquid-water content, the altitude of the base of the cloud, the height of the freezing level, the turbulence within the cloud, and the vertical thickness of the cloud, are all interrelated and must be considered if a proper understanding of cloud reactions is to be expected.

3. The more than 13,000 separate observations made at three-hour intervals of the concentration of ice nuclei which we have made at the Mt. Washington Observatory demonstrate the large variation in the concentration of ice nuclei in the free atmosphere. With a fluctuation of more than a million-fold in these values at $-18^{o}C$, the large differences observed from day to day in the natural seeding of atmospheric clouds become understandable. The maximum values observed at Mt. Washington of 1×10^{7} per cubic meter are not sufficient to cause rapid overseeding effects. Such conditions do occur, however, in the semiarid regions which are the source of many of these natural

ice nuclei. A concentration of ice nuclei of 5×10^7 per cubic meter is required to shift a supercooled cloud to snow within a minute.

Our ice-nuclei studies show that during about 50 percent of the time the concentration of effective nuclei in the northeastern United States is below 1×10^2 per cubic meter. Such a level of ice nuclei is probably inadequate to start a precipitation reaction within the life cycle of a cloud.

4. It is feasible and practical to conduct controlled experiments in the atmosphere and by proper seeding techniques to start reactions in unstable clouds. This provides the meteorologist with a powerful tool for exploring the physical and chemical reactions that lead to storminess.

5. Techniques are now available for determining the concentration of all types of nuclei in the atmosphere. Several of the instrumental methods are completely automatic.

6. Since it has been demonstrated that localized effects due to seeding operations in areas up to 500 square miles are easily produced in unstable cloud systems, it seems reasonable to expect that widespread effects could be initiated with equal effectiveness. Strong evidence that this has already been achieved is presented in the portion of this report prepared by Dr. Langmuir.

7. Experimental flights under a carefully controlled operational procedure have been accomplished with all cloud types and at altitudes ranging from a few thousand feet to more than 30,000 ft. Dry ice and silver iodide seedings in clear air and in cumulus and stratus cloud types have shown that, under conditions that occur frequently, positive reactions may be expected with each specific situation.

8. The effects of seeding operations in the atmosphere range from the formation of snow areas in previously cloud-free air to the removal or further stabilization of stratus clouds and the initiation of the precipitation cycle in cumulus clouds.

9. While conditions under which seeding effects may be produced in cold air supersaturated with respect to ice or in supercooled stratus clouds were found to persist for extended periods, the same is not true with respect to cumulus clouds. The critical period for effectively seeding cumulus clouds seems

to be restricted to the time when the cloud has a vertical thickness above the freezing level of 2000 feet to 5000 feet at the time it is vigorously growing.

10. Since our results indicate that an effective precipitation cycle may be induced in cumulus clouds having tops below 25,000 feet, it follows that hail and lightning storms might be prevented by the judicious seeding of cumulus clouds in cloud-breeding regions. Owing to the rapid growth characteristics of cumulus clouds, the practicality of effectively preventing such storms rests on learning more about the life cycle of typical examples. Whether the answer to an effective hail and lightning prevention program rests in optimum or in overseeding techniques can only be decided after a careful study of the synoptic situation, the importance of the orographic effect in the early stages of storm development, the nature of the clouds, the air flow into the storm area, and time available for conducting seeding operations. Improper seeding techniques could easily aggravate storm damage.

11. The complexity of the mechanisms for the development of an effective precipitation cycle is obvious. Our Puerto Rico studies showed that, long before clouds reached a stage which is ordinarily necessary for the development of rain in continental air masses, rain was falling. We also measured rain intensities of one inch an hour from warm clouds not thicker than 7000 feet with temperatures not colder than $+5^{\circ}C$. Large salt particles in low concentration are probably the cause of such efficient precipitation mechanisms.

The New Mexico studies, on the other hand, often showed the other extreme. Under some conditions, too many ice crystals develop following the inoculation of small cumulus clouds with foreign-particle ice nuclei from dust storms. The resulting precipitation elements evaporate in the dry air before reaching the ground.

At other times, the lack of a sufficient concentration of ice nuclei permits the clouds to grow so high that the upper layers form ice crystals spontaneously. These crystals are so small that their falling velocity is negligible. As a result, they rarely reach the lower levels of the cloud to produce a seeding effect. Plumes of ice crystals, often hundreds of miles long, stream from the tops of such clouds and give visual evidence of the relative inefficiency of

the precipitation process. This latter condition is the dominant one in many regions which receive marginal amounts of rain.

12. Evidence seems to be fairly definite that the source of most foreign-particle ice nuclei is of volcanic origin. Although active vulcanisms plays a minor role as a current source of ice nuclei, most of the "good" samples collected by the writer or sent to him by friends in other parts of the world had their ultimate source in volcanic activity. Few of the aerosols produced by man in his manufacturing processes serve as good ice nuclei, although most of them are excellent condensation nuclei. The role of sea salt seems to be intimately related to warm and cool cloud rains, but such effects tend to fall off rapidly over continental areas.

13. The amount of seeding material that our studies indicate is necesary to produce rapid and effective results in supercooled clouds is the order of 0.5 to one pound per mile of dry ice pellets 1/8 to 1/2 inch in diameter for stratus clouds and clear air, and one to two pounds put into the actively growing portion of a cumulus cloud. Owing to the persistence of silver iodide, 100 to 1000 times less of this material is required under the same condition. Unless the latter is put out as burning charcoal fragments, which have a range of fall similar to dry ice, it may be expected that the rate of reaction will be somewhat slower.

When supercooled stratus clouds are seeded, or clear air supersaturated with respect to ice, the reaction appears in less than 5 minutes -- in most cases within a minute. With actively growing supercooled cumulus 6000 feet to 10,000 feet in total thickness, 2000 feet of which is above the 0°C level, a strong radar echo and visible precipitation at the cloud base may be expected within 20 minutes."

RECOMMENDATIONS

"Although we in the Research Laboratory initiated the proposal to wind up the Project Cirrus atmospheric research program, this was not done because we felt that all of the problems were solved. Project Cirrus, from our standpoint, was an exploratory program in experimental meteorology designed to obtain a rough picture of the possibilities and limitations of this new approach to dynamic meteorology. The accomplishments are indicated in this portion of the report, as well as in that prepared by Dr. Langmuir, and in the 22 Progress

Reports, the 40 Occasional Reports, and the 36 papers published in scientific books and periodicals by the Research Group. As always happens in a basic research program, the solving of one problem poses several new ones. The following suggestions are made to indicate some of the projects that should have further study.

1. Measurements of the concentration of ice nuclei, condensation nuclei, and large salt particles should be inagurated on a regular schedule in a number of key locations throughout the world. This should establish the relative importance of nuclei to the precipitation patterns of various localities.

2. Cloud survey and analysis should be made on a regular and continuing program, especially in regions where rainfall is of a marginal nature. Such a survey could be used to establish whether seeding operations might have economic value.

3. Information is now available so that seeding techniques could be designed as follows:

   a) To clear a solid overcast of supercooled clouds;

   b) To produce a snow area in air supersaturated with respect to ice;

   c) To increase or reduce visibility in supercooled ground fogs;

   d) To initiate or prevent precipitation from orographic cumulus clouds.

4. The single hurricane reconnaissance flight made by Project Cirrus personnel demonstrated that clouds that can be affected by dry ice or silver iodide seeding are likely to occur in such storms. Further seeding studies should be made with such storms, especially in their early formative stages.

5. The results of the New Mexico research indicated the distinct possibility that the precipitation cycle could be induced in cumulus clouds before they had the vertical thickness ordinarily present when cumulus clouds produce damaging hail and lightning. Proper seeding techniques could probably prevent violent storms of these types.

6. Further investigations should be inagurated to establish the feasibility of controlling the particle

sizes in precipitation. Under many conditions, this should be feasible by the proper control of nuclei concentrations, especially if the air is moving into the clouds.

7. Further studies should be made with cirrus cloud systems. The presence of effective condensation nuclei in the air above the top of cirrus clouds might play an important role in the number of cirrus crystals which form. In all such studies, snow-crystal replicas should be made.

8. If randomized experiments are attempted for gathering statistical information in experimental meteorology, the following procedure is recommended. A set of criteria should be decided upon for selecting suitable conditions in the planning phases of the operation. These conditions should be completely objective. The decision to activate or postpone the seeding operation should be selected by the flip of a coin or any other procedure dependent on chance. This decision immediately fixes the procedure for two operations, the immediate one and the next one following. When the third situation arrives, the decision to operate or not to operate is again selected by chance, followed by a fourth operation, which is again opposite to that decided upon by chance. In this manner, the operations are randomized but 50 per cent of them are automatically test operations. Such a procedure is far better than selecting all operations by chance.

Another procedure that appeals to the writer even more than the preceding one is to use the same method of selection but to have alternate objectives, such as optimum seeding and overseeding. Since the desired results are very different if the operations are successful, there should be no difficulty in adequate evaluation. It should be recognized that cloud systems suitable for clean-cut experimental studies are not unlimited in occurrence, so that a realistic approach to experimental studies should be designed to take advantage of all suitable conditions that arise.

9. Anyone who has watched the sky regularly, especially in the regions west of the Mississippi, cannot fail to be impressed with the vast quantity of cirrus clouds that fill the sky, especially from early afternoon until after sunset. Most of these clouds are false cirrus and constitute visible proof of the inefficiency of the precipitation cycle in the regions where they form at the top of towering cumulus. False cirrus streamers hundreds of miles long are common features of the

western sky. Most of them come from the cloud-breeding spots of the mountains. Such clouds represent moisture that is lost to the area where the clouds were formed.

One of the challenging problems in a cloud-seeding program would be the design of an operation with the objective of reducing or even preventing the formation of such clouds. Regions that are ideal for such studies are New Mexico, Arizona, the Black Hills of South Dakota, and Central America.

10. The other problem presenting a real challenge is related to oceanic rain. Precipitation that falls into the ocean represents another inefficient utilization of solar energy. While it is true that the precipitation portion of the hydrologic cycle results in a net gain of heat to the atmosphere, rain or snow falling into the ocean is not of direct value to the continents.

Another interesting and important program would be to investigate the feasibility of overseeding techniques designed to delay or prevent the precipitation cycle in regions over the sea upwind from land areas. This could result in the influx of moister air over the land, which might then be utilized in an effective manner by the use of the seeding techniques described in this report.

Research with respect to this problem should be designed to study the effect of adding additional quantities of condensation or ice nuclei to the atmosphere in cloudy regions over the sea. Places where such experiments could easily be studied are the Olympic Peninsula of northwestern Washington, the Oregon and California coasts, and over islands like Puerto Rico and Hawaii.

11. The intentional addition of an effective concentration of highly efficient ice-crystal nuclei (such as silver iodide) to the air over an area of 50,000 to 100,000 square miles in a region known to be suitable for cyclogenesis, and the subsequent field observations of effects produced, constitute another extremely important aspect of experimental meteorology requiring further study, expecially in the field. A determination of the possibilities and limitations of such operations is of great importance. It is probable that only through such an approach will weather control become a reality. Methods of modifying the circulation pattern of the jet stream should be explored throughly. Such

studies should be made in areas like the region northeast of New Mexico, the Gulf of Alaska, and the southeastern United States.

"The prevention of cirrus formation in towering cumulus, the delay of the precipitation cycle over the ocean, the modification of the circulation pattern of the jet stream, and similar problems will not be solved unless the approach to these problems is made with imagination, enthusiasm, and a thorough knowledge of cloud physics. If such an approach is made, however, the writer is convinced that many important meteorological discoveries will follow."

With this rough indication of the situation in this area of the atmospheric sciences as it existed in 1952, it is pertinent to examine the progress and new discoveries which have been made in this field during the intervening seventeen years. Also, we should consider how to take advantage of the outstanding group of young scientists, engineers and technicians now available, trained and eager to do something in this important and intriguing area of science.

During the first decade following my demonstration on 13 November 1946 (23 years and one day from the time I am writing this paper), there were some persons who wouldn't believe that it was possible to employ dry ice (or silver iodide) to modify natural clouds in the free atmosphere. It took nearly twenty years for my experiment of 25 November 1946 in dispersing a supercooled ground fog, to be recognized as a valid undertaking for clearing supercooled ground fogs or low stratus in the vicinity of airports despite our demonstration of success at the Rome Air Force Base in the Mohawk Valley on 24 November 1948, and our now famous 17 miles long "race track - L" -- "gama" -- and "Figure Four" patterns cut into clouds during that same year. Following these successful demonstrations we even worked up a series of operational procedures for conduting airport clearing operations -- in 1948 -- 21 years ago!

Following my initial seeding with dry ice, Dr. Bernard Vonnegut of our group discovered the effectiveness of silver iodide for producing effects equivalent or even superior to dry ice under some conditions. The acceptance of silver iodide as an effective substance for massive cloud seeding was not as readily accepted by some persons as dry ice even though it was quickly adopted by commercial operators as more adaptable to field operations. However, the debate as to its effectiveness when dispensed from ground generators still occupies the attention of a number of persons and a few diehards continue to deny its usefulness.

Following the termination of Project Cirrus operations (requested by our advisory group in General Electric when we lost our trained pilots due to the Korean War) a number of other field and flight

activities were initiated by other groups in the United States. In other countries noteably Australia, France, Russia, Israel, Japan and Switzerland, intensive studies were started shortly after the announcement of my first laboratory (2) and field experiments (3).

In 1952 at General Electric we disbanded our group whereupon I left to join the Munitalp Foundation and subsequently recruited Ray Falconer, Don Fuquay and Paul MacCready. Bernie Vonnegut and Maynard went to Arthur D. Little where they were joined by Charlie Moore. Duncan Blanchard joined the Woods Hole Oceanographic Institute. Dr. Langmuir retired from General Electric but returned an active interest in weather dynamics and helped me in some of my activities with Jack Barrows in organizing Project Skyfire in the U. S. Forest Service (4). He and I were modelling tradewind clouds shortly before he died in 1957. We all retained a continuing interest in weather modification and continued the friendships nurtured by our earlier work with Dr. Langmuir at G.E.

It was during this period that a number of commerical cloud seeding firms were organized and began to offer services to farmers, ranchers, municipalities, irrigation districts, and similar groups of private and public organizations. In some instances the potentials for weather modification were exaggerated to varying degrees so that after a few years many of the customers became disillusioned. Thus, a considerable proportion of "rain making" as it was sometimes referred to became a subject of questionable merit. Contracts were cancelled and earlier critics were able to say, "I told you so". During this period, however, a number of stubborn and knowledgeable persons, who had the courage of their convictions, stayed in the field quitely conducting their operations, carefully watching the scientific community and adopting new ideas and findings as rapidly as their own experimental trials convinced them of the usefulness of the reported new knowledge. Those who had the fortitude and stick-to-it-iveness through this critical period just ending have developed an operational competence and the reputation of being effective weather engineers. This is about to pay off for these persistent pioneers.

In the early Fifties following the ineffectiveness of some commercial groups to produce obvious changes in the weather pattern they had promised to modify, it became obvious to those interested in obtaining an estimation of the economic value of some of the field operations that it would be desirable to establish proof of the value of the methods then in use.

It was at this time that an intensive effort was made to use statistical methods for testing the operational effectiveness of cloud seeding. This, I now believe, was a major mistake in our procedure. I am sure that some very competent scientists will not agree with this statement. However, I believe strongly in the contention made by Langmuir in 1948 during a meeting at Schenectady sponsored by the National Academy of Sciences that "weather" is

basically a divergent phenomenon -- one that is controlled by a nearly infinite number of small random events. As he said at the time, "It may be far easier to control the weather than to predict it!" Having worked with him for more than a quarter of a century, I was very much aware of his basic philosophy, his ability to take advantage of serendipitous events and his uncanny sense of "guessing" about the basic causes of important scientific phenomena and their interrelationships.

He was in strong agreement with some of the ideas expressed by pioneers such as Findeisen who in 1937 said,

> "The recognition of the fact that quite minute, quantitatively inappreciable elements, are the actual cause setting into operation weather phenomena of the highest magnitude, gives the certainty that, in time, human science will be enabled to effect an artificial control on the course of meteorological phenomena. It would be going beyond the limits of the present work to discuss in detail the possibility of exercising a kind of technical control over the course of weather conditions. From the considerations under survey here, we have now come to quite new points of view on this. It can be boldly stated that at comparatively moderate expense, it will, in time, be possible to bring about rain by scientific means, to obviate the danger of icing, and to prevent the formation of hailstorms. Through the energy transformations thus secured, various other weather phenomena (e.g. temperature, wind) will be brought under a certain kind of control, which perhaps never, in a direct manner could, to an appreciable extent, be acted upon in the atmosphere. The colloido-meteorological investigations, by themselves with the only assistance of research work on the means to get some control over the weather factors, have opened up a new field for their efforts. They obviously only can solve those various problems with the close assistance of aerology."

Dr. Langmuir encouraged me to establish the routine measurement of ice nuclei on the summit of Mt. Washington which started in 1948 and has continued to the present time. In the studies there I found that the concentration of ice nuclei varied by as much as a million fold. If one concedes that the concentration of "natural" ice and cloud nuclei have any relationship to the micro and macrophysics of clouds, it is a logical corollary that the concentration of such particles in the free atmosphere should have some effect on the development of weather and weather systems. If this is true then it is quite obvious that some aspects, at least of meso and synoptic weather systems, could be affected by the randomness of the generating areas of ice and condensation nuclei and the mass movements of these infected air masses. These vary from settling cirrus, dust storms, volcanic eruptions, forest fires, air pollution storms at sea, and other factors most of which cannot be classed as steady or predictable sources of such particles.

Is it any wonder that statistical methods have utterly failed to provide us with clear cut or even hopeful answers to the efficacy of cloud seeding operations? As a complete novice in the complex realm of statistics and statistical methods I still fail to see how these procedures can possibly help us to solve our current problems in testing the effectiveness of weather modification efforts. It is obvious, of course, that if the weather behaved in an orderly and repetitive manner it should be a simple matter to test the effectiveness of some specified procedures using statistical techniques. However, when one is a field man and has spent several decades on mountain tops and other places looking at the variabilities of the day after day weather, it soon becomes clear that there are few things about weather which can be used for making statistical comparisons. In fact, about the only factor which can be controlled in a realistic manner is the intentional seeding process and even this will be modified by the natural or inadvertent sources of nuclei from near and distant air pollution sources.

Thus, I believe the time has arrived when it is necessary to have the courage of our convictions and again resort to private enterprise, economic need and the ingenuity of our United States system to mount a major effort of work with local communities, municipalities, farmers organizations, ski slope operators and others having a big stake in the availability of atmospheric water resources which might be managed in a useful manner.

I am increasingly convinced that if we wait for the university community or the government to mount such an operation, it will never happen. This is not to say that the way will be an easy one! It will be necessary first of all, to solve the "people" problem. This cannot be done entirely by the federal or even the state governments. There is not enough continuity or desire on the part of those involved to get the job done in an effective manner although their services and mechanisms must be utilized. The university community cannot be involved either since they are much more capable by training and interest to become involved in basic rather than applied problems and are not a mission oriented community. Some will have transient interests in such an area but are not likely to have the "follow through" that is essential. Hopefully they can, however, be encouraged to devote considerable energies toward unravelling the complex and often baffling features of natural weather systems and cloud physics.

Only private free enterprise actuated by need and economic advantage is likely to apply the necessary effort to make such a program sucessful. In addition, it will be imperative to have the community likely to benefit from such services actively and intimately involved especially with their pocketbooks. If a proper educational effort is injected into the preliminary plans, I believe that the "people" problem will automatically be solved.

I should hasten to add that at the present time there are a few pioneers who understood all of these aspects of the problem more than

fifteen and even twenty years ago who have not deviated in their objectives or services to the community. If it were not for their enterprise and intestinal fortitude we would now have a much larger job to do to "get going". Nor do I say that statistical methods are of no value whatsoever.

I believe we should be smart enough in sizing up the experiences of the past 23+ years to determine the useful aspects of all the efforts which have been expended during this period so that we can extract from it the useful factors and then collectively and individually reassess the situation and move ahead without further delay. Those who seize this opportunity, and I believe a fair number of them are in the Weather Modification Association, should have an exciting and satisfying future.

One reason why I have been forced to this conclusion is that shortly after World War II, I heard many of my friends in meteorology associated with the government and the academic community say that if they could get a radar network established they would be able to solve the forecasting problem. When a radar network became established and things didn't improve very much we heard that a very large computer was needed if satisfactory forecasts were to be made. Then we were told that weather satellites both moving and in a fixed position above the atmosphere would provide the necessary information. Now we are told that our forecasting problem will be solved by the World Weather Watch. While I presume some improvements have occurred in the course of these developments, I find myself wondering whether Langmuir wasn't right and that there will always be random factors which will forever defy man in his efforts to develop reliable methods of forecasting the weather in the detail that is desired by the average person.

One of the features of nearly all of the rather crude statistical comparisons which have been made of privately or publicly sponsored seeding operations most of which are still underway and have been running from ten to fifteen years, is the evidence in most instances of effects which indicate anomalous but positive precipitation increases during all or most of the operational periods as compared to the historical record. This tends to be the pattern which appears in most instances when the operation is carried out by knowledgeable and capable organizations.

In recent years, the introduction of more and more physical evaluation techniques has supplied us with many cause and effect relationships associated with radar anomolies, silver concentration increases in the fallen precipitation, crystal and structure of snow, concentration and size of snow particles, variation in rate of precipitation induced by the pulse operation of seeding generators, the size patterns of raindrops, and changes in cloud structure. Most of these physical studies can be used to support the evidence of precipitation augmentation by 5 to 20% above the historical target/control patterns.

I believe the time has come when an intensive effort should be

mounted to do everything possible to take advantage of every opportunity to effectively control the weather pattern for some useful objective whether it be for moisture transport, lightning or hail prevention, rain or snowfall augmentation, or similar objectives. There is nothing which need prevent those who wish to conduct physical observations of seeding effects to work in such areas but they should not in any way control the basic objective of the effort to produce economic benefits for the recipients whatever their immediate and long range needs may be.

It is time to get moving!

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WHAT IS OVERSEEDING?

Robert D. Elliott

North American Weather Consultants

1. INTRODUCTION

Through the years, the term "overseeding" has appeared in many places, but in the author's opinion has never been adequately defined. In general, it is implied that cloud seeding reduces precipitation when overseeding occurs, but the role of the various interacting processes of condensation, nucleation, crystal growth, and fallout need more thorough explanation than has been given. Through the use of a numerical model of the ice phase micro-physical process in supercooled cloud, a number of facets of seeding have been revealed. This discussion is based upon these and will, hopefully, shed more light on the matter.

The cloud seeding area-of-effect model (Elliott, 1969) is a steady state model in which the nucleant is dispersed in a plume which drifts up a mountain slope and over the crest, or optionally, is entrained into convection. On rising to lower temperatures, nucleation occurs in a series of 2C steps. Stepwise computations (short time steps) are made of the growth by diffusion and accretion of the ice particles thus formed. Likewise, precipitation is computed for each time step and a water-ice budget is kept. The model includes diffusive mixing, entrainment, and horizontal drift as well as condensation, nucleation, growth, and fallout. It also includes a trans-mountain air flow sub-model.

The input to the model is an upwind sounding, the geometry of the area, and the nucleant source strength, type, and position. When real storm data are run through this model, it predicts a seeding area-of-effect which is in line with observed areas of seeding effect. The model can also be used in simulation experiments where a variety of hypothetical ground or aerial sources under different types of storm environments can be tested. Not only is the area of seeding effect predicted, but the internal workings of the microphysical mechanisms, which are so difficult to observe in nature, are all laid out in plain view in the computer printout. What follows is a general discussion of these internal microphysical processes as revealed by a considerable number of seeding runs on "paper". The model is designed to handle, in a special way, seeding by natural nuclei as well as artificial so that direct comparisons can be made between the effects of natural and artificial nucleation.

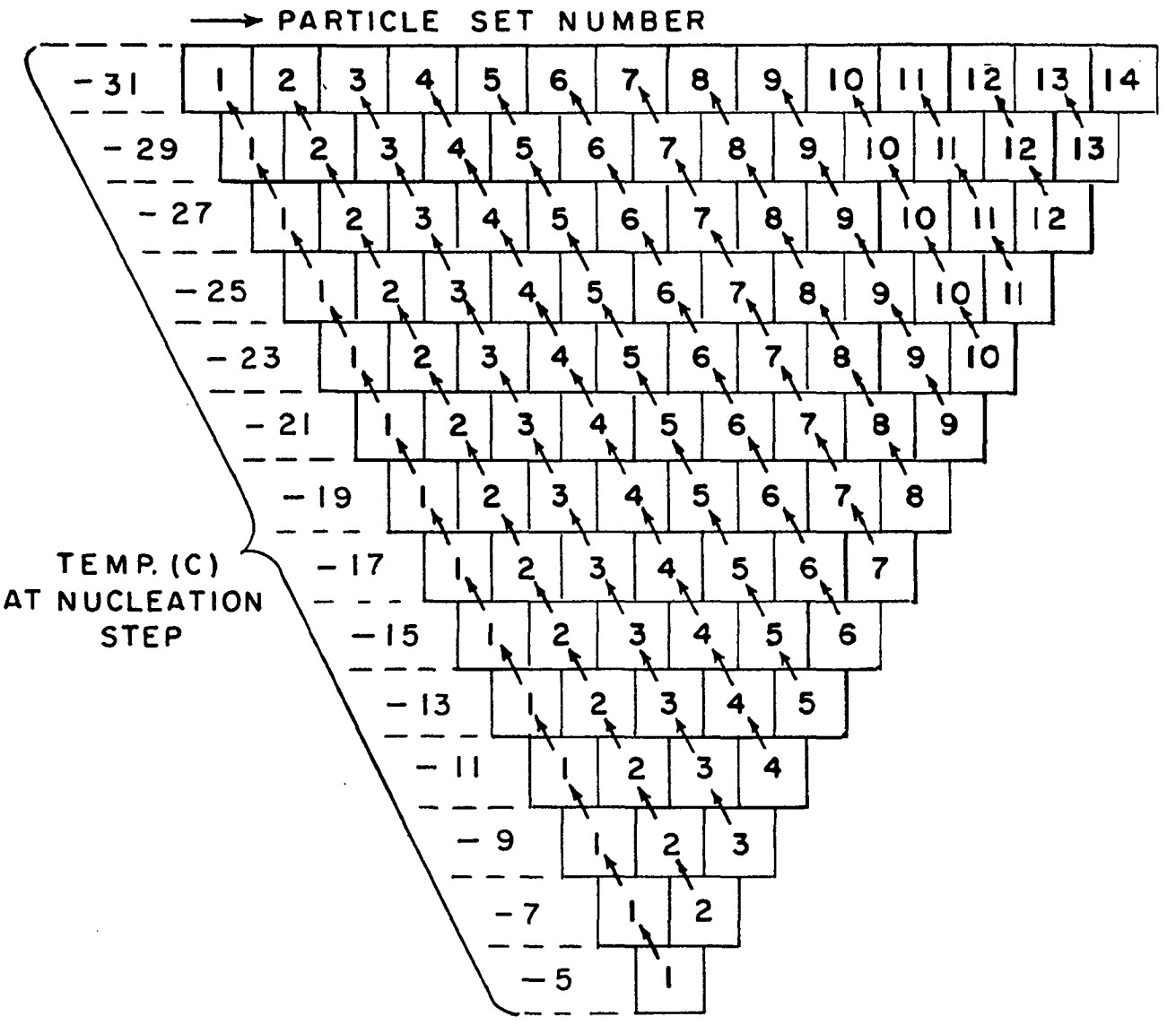
2. INTERNAL MICROPHYSICAL PROCESSES

For the sake of this discussion, we shall define a "standard" wintertime orographic storm situation with embedded convection cells as a case where the cloud base is at 850 mb, the 500 mb temperature at -20C, and the nucleant from a ground plume is wholly entrained and uniformly mixed into a 1 km^2 cross section tilted convection cell with a 3m sec^{-1} mean updraft. On ascending through each 2C nucleation step within this cell, a new set of ice crystals is formed, each set having a uniform mass and concentration at one level, but growing and partially precipitating out on each step along the plume. The precipitated particles are falling out of the lower side of the strongly tilted convection cell. Between each computational step all properties are assumed to be uniformly mixed across a given level.

The internal processes occurring within the convective updraft of the standard case are illustrated by means of four diagrams, Figures 1-4. Each diagram consists of an array of boxes representing each set of ice particles at various nucleation levels. Figure 1 shows the particle set designator numbers for each box. For example, on ascending through the -5C level, set #1 is produced through nucleation (lowest box). On ascending to the -7C level, set #2 is produced. Also at this same level there is the original set #1 particles which have been carried aloft in the updraft and have now grown somewhat by diffusion and accretion. At the -9C level, we have three sets of particles, numbers 1 and 2 being carried along, and the new set number 3 being produced by nucleation. The arrows mark the stepwise upward transport of different particle sets. This process continues with new particles being accumulated at each step, until at the top level there are fourteen sets of particles, each having their own characteristic mass and concentration.

In Figure 2 the particle masses for each set are denoted in each box. At a given level, the earliest formed set (lowest numbered) has had the longest growth time. Thus, largest masses appear in the upper left hand corner of the diagram. They are limited in the model at a mass of 10 mg where tenfold fracturing is initiated. Thus, there is a large area on the upper-left portion of the diagram where mass has fairly uniform values within an order of magnitude down from this limiting mass.

Figure 3 shows the concentration of ice particles for each set in number per cm^2 mb. The unit of volume cm^2 mb is approximately one liter. In the case of natural nucleation shown here, the numbers of new particles (along right side diagonal) activated per step increases almost uniformly on a logarithmic scale except in the lowest levels. In the absence of fracturing, a given particle set might be expected to retain its original concentration except for some depletion due to precipitation and mixing. However, the change in concentration during upward movement is dominated by the fracturing effect so that the concentrations for the lower-numbered sets are increased several orders of magnitude by the time the -31C level is reached.



PARTICLE SET ARRAY

Figure 1

The figures 2 and 3 patterns are typical of model computations for natural nucleation. When artificial nuclei are introduced (in addition to natural nuclei), the boundaries of the mass divisions in Figure 2 are shifted in the manner indicated by the arrow. Masses are greatly reduced, the division lines being shifted well to the left. This change occurs because the available water is shared over many more particles; i.e., growth tends to be limited by the condensation rate more often than in the natural case.

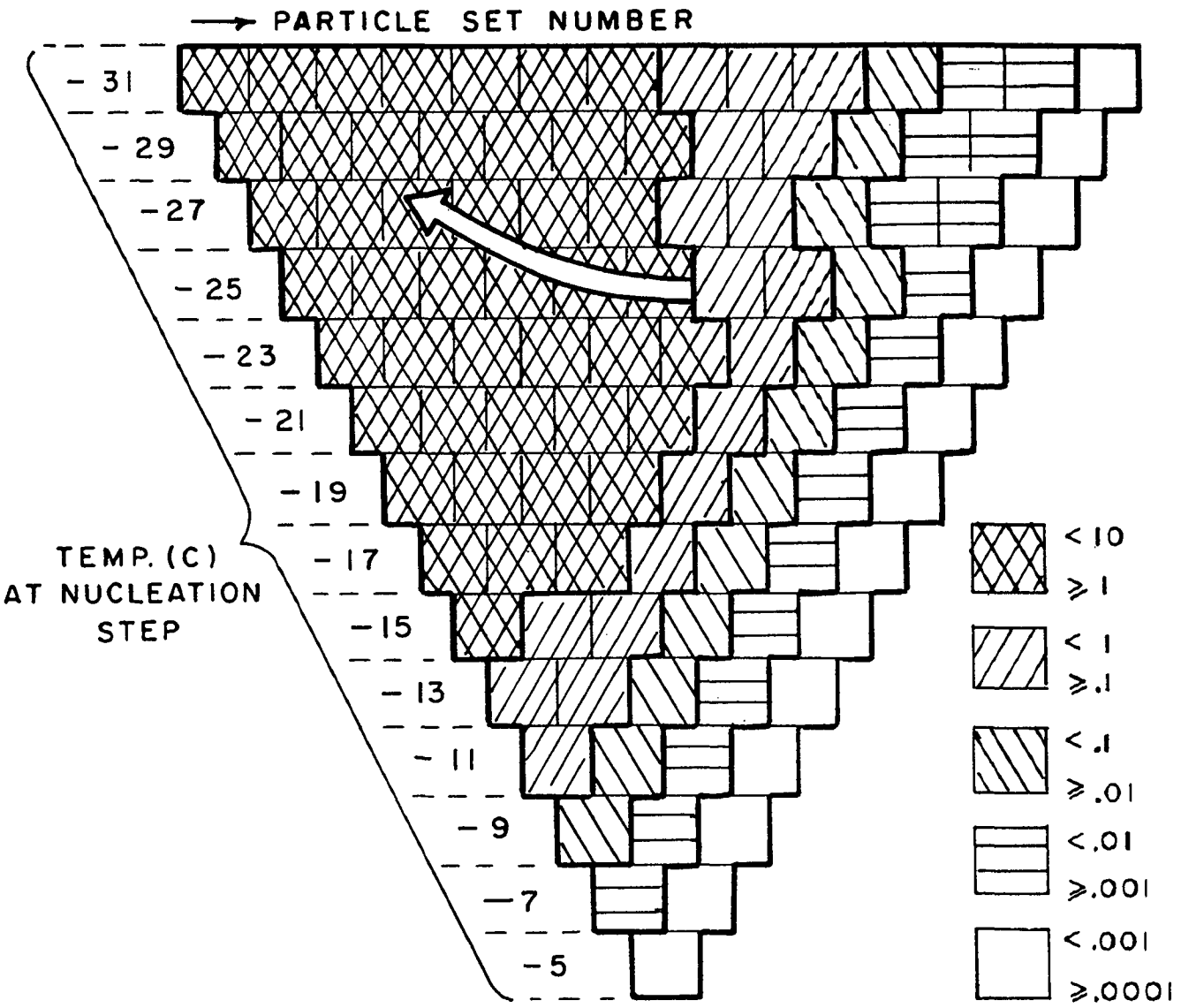
In the case of concentration, seeding increases particle concentrations in lower-middle levels (see Figure 3), but changes it little at high levels where natural nuclei become more abundant than the artificial. The low numbered particle concentrations are even reduced at high levels. This reduction occurs because there is much less fracturing in the seeded case due to the smaller masses. Although the average particle set mass is smaller with seeding, there are many more of the lower numbered sets which have large masses due to long growth.

Precipitation (or rather interception rate on a sloping surface) for a given particle set is directly proportional to the product of the concentration, the mass, and the terminal velocity; the latter being related to the mass in this model. When this is calculated and mapped for the natural case, we obtain the pattern shown in Figure 4. There is a maximum of precipitation contribution from the intermediate numbered particle sets. The large mass particle sets are too few in number, and the sets with a high concentration have too small a mass to contribute significantly to the precipitation.

With seeding, the pattern is shifted as shown by the arrows, with greater precipitation occurring at lower levels. However, at higher levels the precipitation peak in the four to eight numbered portion of the precipitation spectrum is narrower for the seeded than for the natural case because of less fracturing (in the lower numbered sets) and smaller masses (overall).

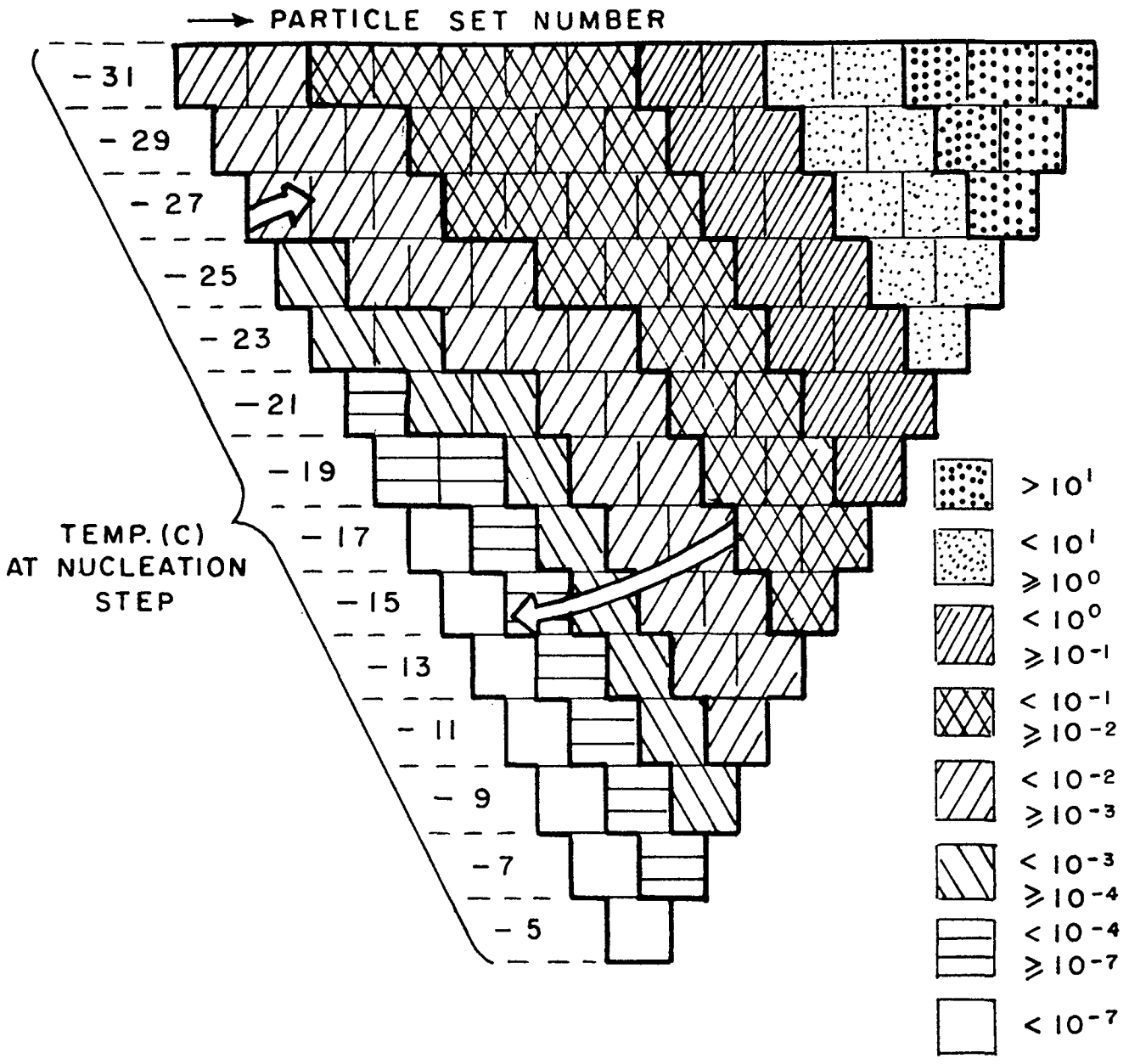
The net precipitation at any level in the updraft is the sum of values across the row of boxes corresponding to that level. In the natural case shown in Figure 4, the net precipitation increases rapidly aloft at first, then more slowly. The seeding-produced modification as indicated by the arrows is to increase the net precipitation markedly in the lower levels, and to reduce it at high levels. Thus, there is a level above which there is more net precipitation in the natural case than in the seeded case. This will be called the level of overseeding. In the standard case it occurs around -30C.

If the net precipitation is summed up the column to a given level and called the total precipitation, then one can find a level where the total natural precipitation exceeds the total seeded precipitation. This occurs at a level a few degrees colder than in the case of the level of overseeding. We shall refer to this as the critical limit.



PARTICLE SET MASS (mg)

Figure 2



PARTICLE SET ICE CONCENTRATION
(NO. cm^{-2} mb^{-1})

Figure 3

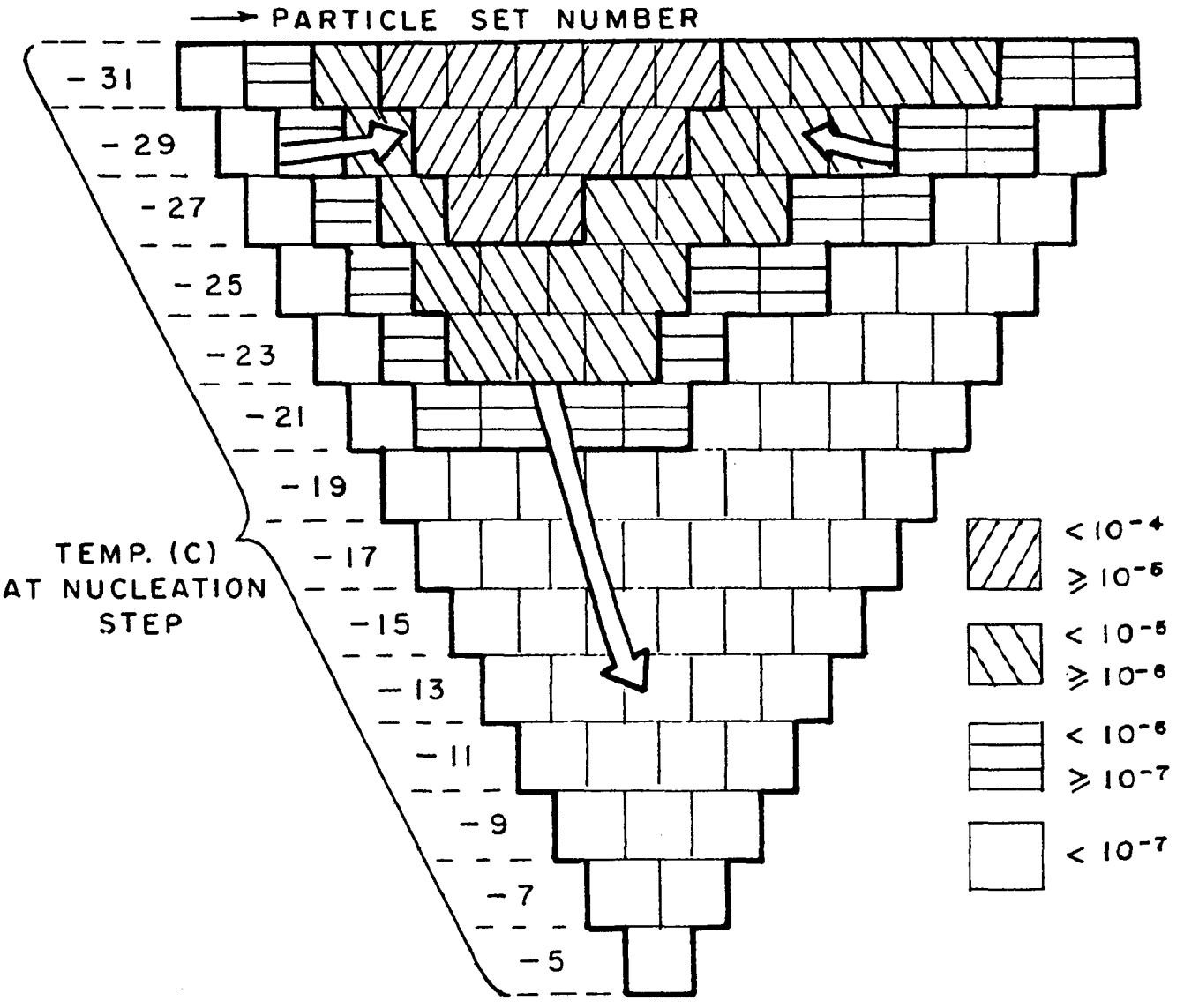

PARTICLE SET NUMBER
-31
-29
-27
-25
-23
-21
-19
-17
-15
-13
-11
-9
-7
-5
TEMP. (C) AT NUCLEATION STEP
< 10⁻⁴ ≥ 10⁻⁵
< 10⁻⁵ ≥ 10⁻⁶
< 10⁻⁶ ≥ 10⁻⁷
< 10⁻⁷
PARTICLE SET PRECIPITATION (gc⁻²s⁻¹)

Figure 4

Calculations for a ground plume drifting and diffusing in the stable air mass under forced orographic ascent produce similar patterns of particle set mass, concentration, and precipitation along the mountain slope. In this case the direct comparison of the computations for a natural source and an artificial source is more problematic in its interpretation. The natural source is far from being a psuedo-point source as was assumed in the case of convection. There are the naturally-produced precipitation particles falling down through the ground plume as well as those activated within the plume itself. However, some useful information can be obtained by using the same approach as was used for convection.

It is interesting to note that with seeding in the ground plume case, the precipitation could be increased along its lower reaches and diminished over the crestline. A seeding system could theoretically be optimized for lower level, higher level, or total precipitation increases across a mountain range. Grant, et al (1968) have developed an equation for determining the optimum concentration for a given location along the plume.

In general, the temperature dependence of the overseeding effect shown by this model fits the temperature dependent seeding-produced increases and decreases found by Grant and Mielke (1967) in their analysis of the Climax experimental data.

3. ADDITIONAL FACTORS

Additional factors beside temperature are of considerable importance in establishing either the level of overseeding, or the critical limit. They include: ascent rate (or condensation rate), source strength and type, and rate of mixing. Each will be discussed in terms of the temperature of the level of overseeding.

When the updraft rate is mild (say 3 cms^{-1}, as in stratiform cloud or in an extremely gentle upslope flow), model runs show a level of overseeding much lower (about 15C warmer) than under standard conditions. The growth rate keeps ahead of the condensation rate so that level-for-level the particle set masses are larger than in the standard case. This enhances the chance of fracturing in the natural case, where particle concentrations are low initially. The updraft is converted to ice at a lower level but has more massive particles than in the standard case. It would appear that stratiform clouds naturally have a high ice-water ratio and that seeding, except at the very warmest possible seeding temperatures, would reduce precipitation by making more numerous and smaller particles.

Even at the warmest temperature, overseeding may occur in cumuliform clouds. Thus, in the accumulation zone near the tops of small warm cumuli where the updraft is small, natural nucleation could produce through the fracturing mechanism an adequate supply of ice particles and any addition of artificial nuclei would overseed the cloud.

Model computations show that when the updraft rate is exceptionally large (say 9 ms^{-1} as in strong convection, or in flow up a steep escarpment), the level of overseeding occurs at a much higher level (lower temperature) than in the standard case. The condensation rate stays ahead of the growth rate so that the updraft contains liquid water to a high level and precipitation processes, natural or artificial, are delayed compared to the standard case. Thus, in the ground plume case, there may be situations where the level of overseeding is reached in a pass area whereas on adjacent crests to either side it is not reached because the slope leading to the pass is less abrupt than that leading to the crest.

In some cold situations, the seeded plume, on going over the barrier crestline, may be composed of ice crystals and supercooled water, and may decrease the crestline precipitation. To the lee of the barrier, the water evaporates in the downdraft. The ice, according to the model, does not. Therefore, seeding under these conditions and assumptions shifts some of the precipitation lost to the crestline over into the downwind valley.

If there is a strong nucleus source, then the water is shared over more particles in the seeded case than in standard conditions, and the level of overseeding occurs at lower (warmer) levels. This lowering of the level need not be disadvantageous in practice. Thus, if the nucleant will not ascent in convection or a ground plume to the limit of overseeding because of convection lid or geometric constraints, there may be an advantage, precipitationwise, in employing a very strong source. A strong source may be desirable in one case, and not in another.

In plumes undergoing slow mixing as compared to the standard, concentrations are higher and the limit of overseeding is lowered. Thus, a narrow-shallow ground plume can overseed at a 10C warmer temperature than a broad-deep plume where concentrations are an order of magnitude less. This points up the need for making the cloud physics computations on the instantaneous plume, not on a time-averaged plume.

An input factor of some significance is the shape of the nucleus production curve. For example, pyrotechnic devices produce a relatively high nucleus output per gram of AgI at warmer temperatures and relatively less at colder temperatures. This leads to a closer-in increase in precipitation and at the same time may raise the level of overseeding.

Field investigators (Grant 1968, Hobbs 1969, Mossop 1967, 1968, 1969, Veal 1969, and Koenig 1967) have found higher ice concentrations than would be expected on the basis of natural nuclei at the supposed nucleation level. The observed ratios of the ice concentrations to predicted values run as high as 10^3 or 10^4 for nucleation temperatures near -10C and do not approach one until nucleation temperature is under -25C.

Because of the fracturing process, the model predicts this effect. This can be verified by examining the model-produced ice concentrations for those particle sets supplying the bulk of the precipitation. When these are compared to the concentrations for the same sets appearing at the time of nucleation for the natural case, we obtain ratios of from 1 to 10^3, with the large ratios appearing in the lower numbered sets. Because of depletion of ice particles due to dispersion and precipitation, we should expect unsplintered sets to have ratios of under one.

When the particles fall from a convection column to the ground through cloudy air, they grow mostly be accretion, and can undergo further fracturing. The model predicts that in the sets contributing most of the ground level precipitation, this additional fracturing is also 1 to 10^3 - fold. Therefore, the combined multiplication of concentration through fracturing may be as much as 10^6 for the low-numbered particle sets.

4. CONCLUSIONS

It is hoped that the above discussion of microphysical behavior as revealed by this model has provided the reader with some useful insights into the so-called overseeding effect. The effect involves subtle balances between different mechanisms. Future models will surely refine or replace this one, but the author sees no prospects of their being any simpler in form. For example, the introduction of temperature-dependent nucleation and growth rates will produce anomalies in concentrations and growth that will be related to the crystal type. The inclusion of the coalescence (warm cloud) process may lead to some modifications important especially in clouds with warm bases.

The present model is applied to a simple parameterized convection case and does not include the dynamic effects produced by buoyancy enhancement. The latter add a whole new dimension to the problem. For example, if the updraft is increased but the top of convection does not rise, precipitation may be reduced because of shorter growth times. On the other hand, if tops are raised, precipitation may be increased, the level of overseeding being higher with the stronger updraft. On a still larger scale, both upwind and downwind mesoscale processes can develop.

In general, the optimization of a seeding strategy for increasing precipitation involves many considerations. Quantitative calculations of effects along the entire plume (or up the convection column) are required. Economic values as well as physical quantities are involved in the optimization procedure. At the present level of development, numerical models should be regarded as useful in producing hypotheses to be checked by physical observations. The results of such observations can then be employed in model improvement, and the improved models

for the design of new experiments. The experimentalist and theoretician are then linked in a productive feed-back loop.

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PYROTECHNIC PRODUCTION OF NUCLEANTS FOR CLOUD MODIFICATION

- PART I. GENERAL PRINCIPLES -

Pierre St.-Amand, Lohr A. Burkardt,
William G. Finnegan, John A. Donnan
and Paul T. Jorgensen

Naval Weapons Center, China Lake, Calif.

ABSTRACT

In order to develop means for modification of clouds as a step to climatic management, the art of pyrotechnics has been applied to the problem of nuclei production and delivery. Pyrotechnics have advantages of easy, precise delivery of very specific agents at reasonable cost. As a by-product of colored smoke production, Dr. Burkardt and Dr. Finnegan began devising means of silver iodide production by reduction of silver iodate. This is done by use of pyrotechnic mixes that can be burned without confinement; propellant mixes that must be burned under pressure; or by gas-generating compounds that disseminate the material at a low temperature.

Both freezing and hygroscopic nuclei were produced. An outline of the research program is presented, showing the type of nucleant available and the practical distribution system for each type.

I. INTRODUCTION

If man is to mold the climate to his desires, he needs tools to do so. The changing of clouds is, at present, one of the first steps in this process. One of the ways in which clouds can be changed is to induce changes in the state of the water in the clouds. Condensation can be controlled to some extent by means of hygroscopic agents, and changes can be induced from the vapor or liquid phase by freezing or sublimation on appropriate agents. A simple, practical means of introducing such nucleants into clouds in appropriate quantities is needed. This series of papers prepared by workers at the Naval Weapons Center and their scientific collaborators elsewhere brings one of the older and blacker arts to bear on this problem. The use of pyrotechnic processes permits the production and delivery of a wide range of nucleants in controllable quantities. A gamut of nucleating materials has been developed. A series of hygroscopic compounds with different vapor pressure lowerings is available. A series of freezing and

sublimation nuclei has been produced so that choices are available to the experimental meteorologist in the activity of the nucleant as a function of temperature.

The advantages of pyrotechnics in weather modification are obvious. Any delivery rate desired can be produced, ranging from milligrams per hour to tons per second. As an example, a strand, burned for ground-level seeding, can be used which will produce 10^{15} nuclei or less per minute, whereas in large storms such as hurricanes, more than 10^{20} nuclei have been released in a space of 6 minutes. Ease of use is another advantage. Materials may be ground-burned; dropped from aircraft; carried on aircraft, drones, kites, or balloons and burned in flight; or they can be used as either propellant or warhead in rockets or artillery shells. Placement of metered quantities in precise locations in clouds is possible. Sufficient quantities of nucleants may be introduced in a short time compared to the life of a cloud, and dynamic effects may be obtained which can greatly alter the behavior of clouds and cloud systems.

The work is by no means complete. We cannot explain in detail all the reactions; control of particle size is still rudimentary, as indeed is control of reaction products. We welcome suggestions as to materials, production methods, and dispersal and delivery techniques.

In this series of articles we have gone into considerable detail about reactions, processes, and formulations, not because we consider them a part of meteorology or even of interest to most meteorologists, but because the knowledge is of importance to the users.

2. MATERIALS

Use of pyrotechnics in weather modification began quite unintentionally in the distant past when black powder began to be used in large quantities. Screening smokes, usually zinc chloride, phosphorus pentoxide, titanium dioxide and chlorosulfonic acid are in reality hygroscopic nucleants that can be used to stabilize fogs or otherwise alter clouds; use of these agents for this purpose has been quite limited, however.

Usually one or more fuels are mixed with one or more oxidizing agents to produce a chemical reaction that results in heat, light, smoke, trouble, or some other desired end product. The commonest pyrotechnic is black gunpowder, an intimate mixture of potassium nitrate, charcoal, and sulfur. Although used for 2,000 years now, this combination is still not well understood. It serves as the base for most pyrotechnic systems in general use; other substances are added to give colored lights, colored smoke, etc. Many variations are possible, and some of these are extremely sophisticated.

It was while working on the production of colored smokes that Dr. Burkardt and Dr. Finnegan of NWC struck on the idea of generating

silver iodide pyrotechnically by means of silver iodate. They had been developing a compound that produced a metallic mercury smoke and had also developed a system for the production of free iodine and lead iodide, for use in experiments in the high atmosphere and outer space. They foresaw a similar possibility for the production of silver iodide, and in early 1958, made silver iodide smoke by means of a mixture of polyvinylmethyltetrazole (PVMT) and silver iodate. This first compound is still one of the best ever developed because it produced no solid products except silver iodide and burned in a very satisfactory manner. The materials were expensive and processing was difficult, but the way to proceed was clearly indicated. A long development period followed, and the subsequent work is the subject of this series of documents.

The development took several trends as shown in Fig. 1. At this point it is well to call attention to an arbitrary distinction that we use in these papers that may not be clear to the reader. We refer to pyrotechnic mixes and to propellant mixes and to gas-generating mixes. These distinctions are arbitrary and are based on the amount of gas produced by the compositions.

Pyrotechnic mixes. Pyrotechnic materials usually are not intended to produce much gas when burned; a notable exception, of course, is black powder, which is also a propellant. Pyrotechnic compounds usually produce heat, light, and gaseous and solid smoke products, They are made, in general, of an intimate mixture of dry powdered material held together with a relatively small amount of organic binder such as shellac, cellulose nitrate, albumin, or similar material. Attempts to burn these compounds under pressure usually result in greatly increased burning rate and explosion. Because the production of very much gas brings about adiabatic cooling of the burning surface, it is difficult to ignite these materials at ambient pressure at altitudes in excess of 20,000 feet, and special attention must be paid to preparing mixes that burn with the production of very little gas, especially in the igniter and first-fire compositions.

Propellant mixes. Propellant mixes are the usual rocket fuels; these are intended to produce abundant gas at high temperatures. The fuel in these compounds is commonly an organic binder and may consist of nitrocellulose, nitroglycerin in combination with nitrocellulose, polybutadiene, fluorocarbons, or numerous similar materials. Propellant mixes can usually be burned under pressure, and, although the burning rate is a function of pressure, it can be adjusted to not rise excessively, and stable burning is possible. These mixtures may be burned at ambient pressure, but they are more reliable when burned in a closed container. When they are properly contained and have a satisfactory ignition system, they may be ignited and burned at any altitude. The use of the plastic-base materials makes it possible to cast, mold and extrude these products.

Gas-generating substances. A third class of materials consists of gas-generating substances. These are not intended to produce heat or

light as such but are used as sources of copious amounts of gas. These materials serve as dispersants for themselves and for other materials. Examples are colored smoke grenades or devices for dissemination of silver iodide, organic nucleants, or other material at a low temperature. We have not used these compounds widely, but they could be useful.

3. DEVELOPMENT OF SEEDING MATERIALS

Referring now to Fig. 1, we note that two basic classes of seeding materials are produced--freezing and sublimation nuclei and hygroscopic nuclei. The first of these has been mainly silver and lead iodide; the second class has been mainly soluble chlorides and iodides of various metals.

Both classes of nucleants have been prepared in pyrotechnic and in propellant mixes, depending primarily on the means of dispersal to be employed. In general, the propellant mixes are more expensive than the pyrotechnic mixes, but they also have been more effective in the number of nuclei produced per gram. The output is usually purer. This is not important for large-scale use, but it can be important for research applications.

The production of nuclei by the propellant technique began with the use of nitrasol binders, high-energy fuels employing nitrocellulose and, to some extent, nitroglycerin. Use of nitrasols had to be temporarily abandoned because of a series of explosions in other laboratories. As a result, a polyethylene formulation was developed and tested. Large-scale use of polybutadiene proved feasible, and considerable work was done with this compound. Later on, work was begun on fluorocarbon-magnesium mixes, which proved to be excellent from a standpoint of ease of extrusion, permitting fabrication of long-burning strands. A solvent-casting process for the production of lead iodide proved quite feasible.

The development of the pyrotechnic mixes continued concurrently with that of the propellant formulations, and a number of very successful mixtures were produced. At first stoichiometric proportions of oxidizer and fuel were used, but gradually, in the interests of improved effectiveness and proper handling properties, a series of mixtures was produced in which lower proportions of silver iodate were used.

4. PRECAUTIONS

A word of warning may be unnecessary to most readers but may not be amiss for some who may wish to make their own pyrotechnics. The mixtures described in the succeeding papers are all dangerous if not properly handled. Mixing and firing pyrotechnics is safe only when done under proper conditions, and these should be rigorously observed. Advice should be sought from someone skilled in the field

before undertaking such work. Pyrotechnic-grade magnesium is specially hazardous; some mixtures that are safe with aluminum are explosive when magnesium is used. Compounds that take up water of hydration are dangerous when used with magnesium. All compounds finally adapted for use by our group have undergone rigorous testing for safety. It is possible to construct devices that may be safe under one condition of use and hazardous under other conditions. In no case should a loose powder or pressed pyrotechnic be burned under pressure. Racks, dispensers, and containers have to be designed with several fail-safe aspects. Accidental ignition must be carefully guarded against because the heat generated by most of these materials is considerable, the fire usually cannot be extinguished, and damage could easily result. With proper use, no great hazard is present, and a wary user will not be in any appreciable danger from the devices.

5. CLOUD MODIFICATION WORK AT NWC

The work at NWC began with the development of devices for use in hurricanes in Project Cyclops, which later became Project Stormfury. The other aspects were carried forward as fast as financing could be found. We began at the wrong end of the program because at that time it was the only way to make an effective start in view of the resistance in many quarters to weather modification work in general, the feeling of some weather modifiers that the ability to produce ample nucleants was already in hand, the resistance by some to the use of pyrotechnics to produce nucleants, and a widespread feeling within the scientific community that only theoretical work should be done at that time and that a complete theory should precede development of such devices. We have never countenanced that viewpoint for we feel that development and field trials add to understanding and lend impetus to theoretical work, which usually runs behind discovery and development.

At first we felt that sublimation was the most important process in reducing water vapor to ice, and, on the basis of Fletcher's theory, we tried to make particle sizes between 0.1 and 1.0μ in order to induce sublimation at as high a temperature as possible.

It was necessary to test the nucleants, and by late 1961 we began negotiations to have proper tests made by Dr. V. J. Schaefer's laboratory; these had to be abandoned for reasons beyond the control of either party. Negotiations for tests at Colorado State University were begun later, and a test facility was developed locally. Most of the tests reported in these articles were done by M. L. Grant and R. L. Steele at Colorado State University. Because we felt that the then popular practice of reporting activity at only one temperature, -20C, was misleading, the tests were conducted over the temperature range from -4C to -20C so that activity as a function of temperature could be studied. This proved very revealing, because it soon became obvious that contact nucleation, condensation, and freezing effects were far more important at the warmer temperatures than were effects of sublimation, and our development procedure was accordingly altered.

The numerical efficiency of the pyrotechnic process in producing high numbers of nuclei per gram is now competitive with, or better than, any of the other generators in common use, and the delivery rates in terms of total numbers of nuclei delivered are far in excess of more conventional techniques. The effectiveness at warmer temperatures is greater, and the materials that are not deteriorated by moist air can be produced.

Cost of usable items is still high, but this will ultimately be reduced by engineering production work and by mass production; even so, the expense of aircraft operation usually more than outweighs the cost of the nucleating material, and ease of operation becomes an important factor.

6. ACKNOWLEDGEMENTS

It is not possible to list all the people, both in and out of NWC, who have contributed to this work. Dr. Wm. B. McLean, Dr. W. S. McEwan, Dr. C. E. Waring, Dr. E. S. Lamar, Dr. H. W. Hunter, Dr. T. E. Phipps, and others made it possible to proceed with the work. Numerous Navy personnel including Capt. Charles Blenman, Jr., Capt. W. R. Eason, Capt. R. W. Calland, RAdm. F. L. Ashworth, Lt. F. O. Baty, LCdr. R. G. Douglas, and Cdr. R. E. Weidner contributed strongly to the actual development of the project. Captain C. O. Holmquist aided immeasurably by encouragement and administrative help and indeed flew several of our original tests of airborne materials. Captain W. C. Houston also aided immeasurably.

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W. U. Garstka of the Bureau of Reclamation was very helpful to us; his vision and encouragement were invaluable.

As we discuss individual contributions, care will be taken to point out the roles played by our colleagues, but it is inevitable that some will be missed; for this we apologize. The work described herein is not the work of the authors alone but of our colleagues and associates. It has been and still is a gestalt effort in the established tradition of the Naval Weapons Center.

In the succeeding papers, the people primarily responsible for a particular aspect have written it up somewhat independently. However, it should be remembered that one phase is not necessarily distinct from another and the several efforts should be considered as part of a whole.

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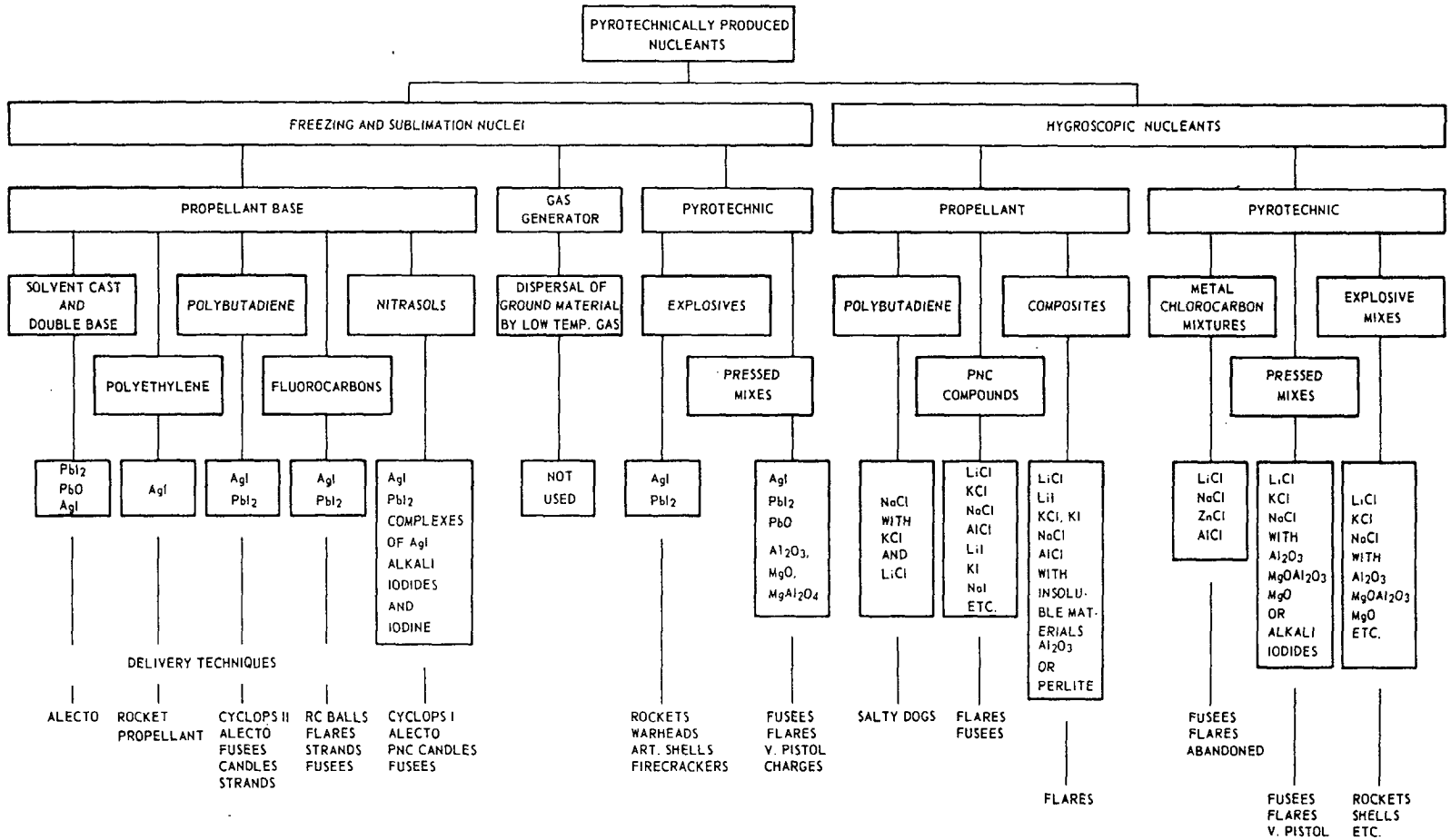
PYROTECHNICALLY PRODUCED NUCLEANTS
FREEZING AND SUBLIMATION NUCLEI
HYGROSCOPIC NUCLEANTS
PROPELLANT BASE
GAS GENERATOR
PYROTECHNIC
PROPELLANT
PYROTECHNIC
SOLVENT CAST AND DOUBLE BASE
POLYBUTADIENE
NITRASOLS
DISPERSAL OF GROUND MATERIAL BY LOW TEMP. GAS
EXPLOSIVES
POLYBUTADIENE
COMPOSITES
METAL CHLOROCARBON MIXTURES
EXPLOSIVE MIXES
POLYETHYLENE
FLUOROCARBONS
PRESSED MIXES
PNC COMPOUNDS
PRESSED MIXES
PbI2 PbO AgI
AgI
AgI PbI2
AgI PbI2
AgI PbI2 COMPLEXES OF AgI ALKALI IODIDES AND IODINE
NOT USED
AgI PbI2
AgI PbI2 PbO Al2O3, MgO, MgAl2O4
NaCl WITH KCl AND LiCl
LiCl KCl NaCl AlCl LiI KI NaI ETC.
LiCl LiI KCl, KI NaCl AlCl WITH INSOLUBLE MATERIALS Al2O3 OR PERLITE
LiCl NaCl ZnCl AlCl
LiCl KCl NaCl WITH Al2O3 MgOAl2O3 MgO OR ALKALI IODIDES
LiCl KCl NaCl WITH Al2O3 MgOAl2O3 MgO ETC.
DELIVERY TECHNIQUES
ALECTO
ROCKET PROPELLANT
CYCLOPS II ALECTO FUSEES CANDLES STRANDS
RC BALLS FLARES STRANDS FUSEES
CYCLOPS I ALECTO PNC CANDLES FUSEES
ROCKETS WARHEADS ART. SHELLS FIRECRACKERS
FUSEES FLARES V. PISTOL CHARGES
SALTY DOGS
FLARES FUSEES
FLARES
FUSEES FLARES ABANDONED
FUSEES FLARES V. PISTOL
ROCKETS SHELLS ETC.

PYROTECHNIC PRODUCTION OF NUCLEANTS FOR CLOUD MODIFICATION

PART II. Pyrotechnic Compounds and Delivery Systems for Freezing Nucleants

Pierre St.-Amand, Lohr A. Burkardt, William G. Finnegan, L. Lee Wilson, Shelden D. Elliott, Jr., and Paul T. Jorgensen.

Naval Weapons Center, China Lake, Calif.

ABSTRACT

The pyrotechnic systems in general use are discussed. Three techniques are in common use: (1) production of AgI smoke by thermal dissemination, (2) dispersal of AgI by gas-generating compounds, and (3) evaporation and/or combustion of solutions of silver iodide and/or a complex of AgI and an alkali iodide. Systems 1 and 2 produce AgI and other combustion products. System 3, with one exception, produces a complex of AgI and alkali iodide.

Formulations are given for production of AgI and some complexes, aluminum and magnesium oxideand ruby spinel. Lead iodide is rarely produced pryotechnically; usually a lead oxyiodide results that also serves as an effective nucleant.

Delivery techniques are reviewed.

I INTRODUCTION

Following the announcement by Vonnegut (1947) that crystallites of silver iodide or lead iodide could cause freezing of supercooled water and induce freezing in supercooled clouds, many techniques were evolved for the production of silver iodide smoke. It has been produced by use of an electrical spark between silver electrodes in an iodine atmosphere; evaporation of silver iodide from heated wires; vaporization by a small electric furnace; burning of silver iodide in a pyrotechnic such as a railroad flare; vaporization of silver iodide or the complex AgI·KI from impregnated string burned in a gas flame; burning of the complex AgI·KI in an acetone or other solution; burning of charcoal or coke impregnated with silver iodide or the complex; burning of a celluloid film, toilet tissue, or confetti impregnated with silver iodide; vaporization of a solution of silver iodide or of the complex in liquid ammonia; Vonnegut (1957).

2. HISTORICAL BACKGROUND

An acetone-burning generator that can deliver the complex

salt, AgI·KI, or 2AgI·NaI, was developed by Vonnegut and Maynard (1952). The idea served as the basis for many subsequent designs by others. The best known is the Skyfire Generator developed by Fuquay and Wells (1957) and Fuquay (1960); recently Roger Steele developed a unit using a solution of silver iodide in isopropylamine that should deliver pure silver iodide.

Balabanova et al. (1959) have generated silver and lead iodides by burning mixtures of red phosphorus and one or the other of the iodides. Balabanova and Vyadrov (1961) have used aerial flares made from red phosphorus and silver iodide and from silver iodide and gunpowder; they have also added silver iodide to a fairly standard green flare mix:

	Composition (wt. %)
Silver Iodide	52.1
Potassium nitrate	18.7
Aluminum powder	5.2
Magnesium powder	4.2
Barium oxide	19.8

This mixture is successful -- there is some question as to the exact composition of the products. The barium oxide was originally added to color the flame; its effect on the silver iodide is not known at present. The potassium nitrate would help the silver iodide particles to serve as condensation nuclei at warmer temperatures.

Nikandrov (1963) described the following formulation for solid fuel torches used to introduce silver iodide nuclei into clouds:

	Composition (wt. %)
Barium nitrate	49.2
Aluminum powder	5.6
Dextrine	12.3
Metallic dust (Mg ?)	28.8
Silver Iodide	4.1

A review of such devices is given by Nikolay Sergeylvich Shiskin (1964) in Chapter 10 of this book. He includes some formulations by other workers. One used by M. Ia. Akensov is:

	Composition (wt. %)
Ammonium perchlorate	40
Iditol	10
Silver iodide	50

This material is reported to give 2 x 10^{12} nuclei per gram of silver iodide at -10C. The use of the perchlorate, an otherwise excellent oxidizer, may give rise to some silver chloride as well as silver iodide. Iditol is a phenol-formaldehyde resin related to Bakelite. A similar formulation was used with lead diiodide, Akensov (1962a and b).

Soulage (1962) reports use of a parachute-activated silver iodide flare using "a pyrotechnic enriched with AgI." Flare compounds prepared by Olin Mathieson Chemical Corp. have been used in this country by Thomas Henderson of Fresno, Calif. Olin Mathieson now has a standard line of pyrotechnic cloud seeding materials (Flare for rain-making, 1968). Atlantic Research Corp. is also actively engaged in similar work. Irving Krick has for many years used coke treated with silver iodide and pyrotechnic fusees quite similar to ours, but details are not available. The foregoing pyrotechnic devices rely on thermal dissemination of silver iodide or lead iodide using a separate fuel-oxider composition as a heat source.

Rockets for use against hail have been developed and used in Italy. Originally the rockets were driven by black powder and used a black powder warhead. A recent change, shown by Khrigian (1963, p. 304) uses a black powder motor and an explosive charge of cheddite impregnated with 2% silver iodide. Cheddite, a mixture of potassium perchlorate and paraffin, is often used for do-it-yourself warfare.

In 1949, Dr. Thomas Stevenson of the Pittman-Dunn Laboratory at the U. S. Army's Frankford Arsenal developed and manufactured cloud seeding bullets. Several compounds were tried. These consisted of delay ignition mixes and tracer compositions to which was added silver iodide. These should have been very effective seeding materials. The formulae for the two most used are given below:

I 460	Composition (wt. %)
Strontium peroxide	85.5
Calcium resinate	9.5
Silver iodide	5.0

This mixture was wet-blended with carbon tetrachloride as a diluent and pressed into projectiles after drying.

CS 49	Composition (wt %)
Potassium perchlorate	73
Powdered Lucite	17
Asphaltum	5
Silver iodide	5

This mixture was dry-blended and pressed into 20-mm projectiles. A standard ignition mixture was pressed over the open end of the CS charge to ensure reliable ignition.

Both 20-mm and 0.50-inch projectiles were used. The .50-caliber bullets contained between 4.6 and 5.2 g of I 460 (about 0.26 g of silver iodide) and burned statically for 13 sec and in flight for about 1.2 km. The 20-mm shells contained between 23 and 26 g of I 460 or CS 49 (about 1.25 g of silver iodide). The 20-mm shells charged with CS 49 burned statically for 101 sec, but in flight the burning time would have been a little less because of effects of spin on the burning rate; these effects might or might not have been offset by effects of altitude and dynamic pressure. The projectiles were tested by firing through a cardboard cold chamber containing a supercooled cloud which was successfully nucleated by even the small amount of material left by the bullet in its flight. We estimate that, at -20C, about 2×10^{10} nuclei per meter would be produced by a .50-caliber projectile so loaded and considerably more by a 20-mm shell. This method of applying nucleants could by made into a very effective system provided self-consuming projectiles could be developed. Dr. Stevenson designed some totally combustible projectiles for both .50-caliber and 20-mm projectiles as well as some projectiles for delivery of liquid carbon dioxide.

The most sophisticated dispersion system described heretofore is "Weathercord", which is "Primacord" containing silver iodide. Primacord is a ropelike material consisting of a hollow waterproof cloth cord filled with an explosive. It is used for simultaneously fuzing charges separated by a distance, and for demolition. Weathercord uses 3.2 g of PETN (pentaerythritol tetranitrate) and 0.8 g of silver iodide per foot of cord. The authors (Goyer, Grant and Henderson, 1966) give the impressive nucleation efficiency of about 5×10^{13} nuclei per gram at -20C. The two examples that they give of seeding clouds indicate that the effectiveness is still very high at -10C. They dispersed the material from aircraft using a Bickford fuze to burn through a string that releases a rubber band used to secure a split cylindrical cardboard container from which the charge and a parachute are deployed. The charge is extended by gravity and the drag of the parachute. It is ultimately detonated by a blasting cap ignited by the remainder of the fuze. The material could be made into bombs, hand grenades, or rocket warheads; it seems ideal for almost any application where dissemination by explosion is called for, provided a safe dispensing system is employed.

3. SILVER IODIDE PRODUCTION SYSTEMS

A complete review of all of these systems would be a lengthy task. Summaries have been given by Vonnegut (1957), by Fuquay (1960) and by others. These schemes have usually fallen into three categories: (1) the production of silver iodide smoke by thermal dissemination of silver iodide, (2) the dispersal of silver iodide by a gas-generating compound that burns or decomposes at a low temperature and disseminates the already powdered silver iodide without physical change, and (3) the evaporation or combustion of a solution of a complex of silver iodide and an alkali iodide.

The first of these three systems produces silver iodide smoke and some free silver and iodine, together with combustion products of the material used to supply head to the reaction. Depending on the material used, a very pure silver iodide smoke can be produced, or, as has been the case in some pyrotechnic smokes, a very complicated product is obtained. The second system produces an aerosol of silver iodide particles and combustion products. The third system produces a little pure silver iodide, but mainly develops a sintered mixture of silver iodide and the alkali iodide; in the presence of water vapor; this mixture reacts to produce the same complex that was used to cause the silver iodide to dissolve in the original solution, usually $AgI \cdot KI$. This material serves as a hygroscopic nucleant, causing a saturated solution of the complex to form, from which, with increased dilution, silver iodide is precipitated. The precipitation of silver iodide or the presence of excess silver iodide causes the droplets to freeze, resulting in frozen droplets that eventually become snowflakes. These units produce some free silver, iodine, alkali oxides, carbonates and iodides as well as the complex. The process leads to an efficient unit if properly used.

The systems described herein for production of silver iodide use scheme (1) except that instead of, or in addition to, silver iodide, silver iodate is used as an oxidizer in a pyrotechnic or rocket-fuel mix. The method was originally invented by Dr. Burkardt and Dr. Finnegan in 1956 and has been developed at the Naval Weapons Center into a number of useful devices. Development of dry-mix pyrotechnics has been carried out locally in a manner parallel to the development of propellant compounds by pyrotechnic chemists, B. A. Breslow and A. T. Wiebke of the Propulsion Development Department; by Dr. S. D. Elliott, Jr., and L. E. Humiston of the Research Department, by G. V. Binns, J. B. Burmeister and R. C. Noles of the Engineering Department. Test units were manufactured, and several different formulations were developed by L. L. Wilson of the Wilson Engineering Co., Hollister, California.

4. LEAD IODIDE

Lead iodide has been formed by means of pyrotechnics and identified. The reaction is not so simple, however, as it is with silver because a number of oxides and oxyiodides of lead are also formed.

In general, stoichiometric mixes yield lead iodide, but overoxidized mixes yield more lead monoxide and some as yet unidentified compounds. The smoke serves as a good nucleant, and the material is quite useful. The reaction can be controlled to some extent by increasing the proportions of iodine and decreasing the oxygen. If used with aluminum and magnesium, a lead spinel might result as well.

5. PYROTECHNIC COMPOUNDS

In general, finely ground silver iodate is used as an oxidizer to burn a fuel. The fuel may be an organic compound or a metal such as megnesium or aluminum. It is important for the best yields of silver iodide that none of the ingredients form stable compounds with silver or with iodine. Within these restrictions an almost infinite number of combinations of chemicals is possible. Several hundred variations have been tried in an effort to control particle size and hygroscopicity of the smoke and to ensure safe burning and storage characteristics, proper physical properties and reasonable cost.

The simplest composition is an explosive mixture of loose grains of pyrotechnic-grade magnesium and finely ground silver iodate or lead iodate. This composition has been used as a burster charge in small rockets, in large cherry bombs and in plastic hand grenades. It may be ignited by a firecracker fuze. The mixture is sensitive and quite dangerous, and it should be kept dry. The reaction is

$$AgIO_3 + 3Mg \longrightarrow AgI + 30 + 3Mg \longrightarrow AgI + 3MgO$$

The yield of silver iodide is 66% of the formula weight.

Nuclei counts are not presently available for the above composition. Upon explosion, a 100-g charge forms a yellowish cloud about 10 m in diameter. The particles are probably about 0.1μ in diameter. The visibility of the cloud is greatly enhanced by the white magnesium oxide.

A rapid burning composition suitable for a pressed flare or fusee for use at high altitudes is Formula 111.

Formula 111	Composition (wt. %)
Silver iodate	84
Magnesium	8
Binder	8

This produces 61% by weight of silver iodide. The smoke is yellowish in color, and the visibility is enhanced by the magnesium oxide.

Slower burning mixtures may be made with aluminum.

The reaction with aluminum is

$$AgIO_3 + 2Al \longrightarrow AgI + Al_2O_3$$

Stoichiometric proportions are

	Composition (wt. %)
Silver iodate	84
Aluminum	16

Formula 114 is formulated as follows:

Formula 114	Composition (wt. %)
Silver iodate	79
Aluminum	14
Binder	7

Mixtures containing only aluminum and silver iodate are hard to ignite and some such as Formula 114 burn poorly, so enough magnesium is usually added to ensure an easy ignition and a quiet burn. An example of a practical formula is

LW 83	Composition (wt. %)
Silver iodate	78
Aluminum	12
Magnesium	4
Binder	6

This reaction is $AgIO_3 + 2Al \longrightarrow AgI + MgO \cdot 2Al_2O_3$. The solid products are silver iodide, spinel ($MgO \cdot 2Al_2O_3$), and a mixture of the oxides of magnesium and aluminum.

Whereas LW 83 has a maximum amount of silver iodide for a stoichiometric composition, it is frequently desirable to decrease the amount of AgI in a mixture in order to reduce the particle size, or to be assured of producing a hygroscopic wetting agent to go along with the AgI. To this end a convenient technique is to mix a stoichiometrically balanced compound that produces silver iodide with another stoichiometric composition that does not do so. Thus it is possible to arrange to have uniform burning properties over a wide range of silver iodide concentration in the composition. A series of such compositions

is available from 78% AgI equivalent to as little as may be desired. From experience it appears that compositions with about 20% AgI are most effective. One such mix that works well from a standpoint of nucleating ability, burning quality, residual ash and safety is formulation 2AL2:

2AL2	Composition (wt %)
Silver iodate	28
Potassium nitrate	44
Magnesium	11
Aluminum	11
Binder	6

The smoke from formulation 2AL2 is yellowish white in color and consists of a mixture of silver iodide, potassium oxide, magnesium oxide and aluminum oxide. To a slight extent it is wasteful of silver because of the tendency of the potassium to scavenge any free iodine, released through decomposition of AgI.

A formulation suited for production of a mixed condensation and freezing nuclei can be made as follows:

$$AgIO_3 + 3KIO_3 + 3Mg + 6Al \longrightarrow AgI + 3KI + MgO \cdot Al_2O_3$$

The proportions are

LW 38H	Composition (wt. %)
Silver iodate	36
Potassium iodate	29
Magnesium	9
Aluminum	20
Binder	6

This material produces mainly an admixture of potassium iodide and silver iodide and serves as a contact or condensation-freezing nucleant. The other solid products are a little potassium monoxide, potassium carbonate and some spinel ($MgO \cdot Al_2O_3$). This formulation can be adjusted to change the warmest temperature at which it works by varying the ratio of silver iodate to potassium iodate.

The question of the solid products produced other than silver iodide is important. Magnesium oxide and aluminum oxide are quite inert. They are insoluble and do not participate readily in reactions

with either silver or iodine. Both serve as additional sublimation nuclei at colder temperatures. Fukuta (1958) gives -9.3C as the threshold for the freezing of water upon magnesium oxide particles and -6.5C for aluminum oxide. If an alkali or other material that gives rise to hygroscopic products is used, the adhering of some of this material to either oxide could cause it to act as condensation-freezing nuclei. Aluminum oxide tested at -20C at Colorado State University gave 4 x 10^{13} nuclei per gram of aluminum.

Charles Drew et al. (1964) have shown that aluminum oxides produced from the combustion of aluminum powder consist of spheres of a variety of sizes dependent primarily upon the size of the starting material and the nature of the environmental flame gases.

The oxides produced occur in two particle size distributions. The larger material consisting of spheres 1 to 100μ in diameter is believed to be produced from accumulations of oxide on the particle surface during combustion. The smaller material comprising perhaps 30% of the oxide produced is spherical powder usually less than 1μ with the smallest considerably less than 50 Å diameter.

Under some conditions, thin walled, hollow spheres are produced which reach a maximum of about three times the diameter of the original particle of aluminum. For example, with a 100-μ diameter starting material, 300μ-diameter bubbles have been measured.

If a mixture of aluminum and magnesium is used, spinel is produced, its yield being dependent on the ratio of aluminum to magnesium in the combustion process. Spinel is a family of minerals having the formula

II	III		II	III
R	R_2O_4	or	R O	R_2O_3

It is isometrically crystallized, usually in octahedrons. The commonest member of this family is $MgO \cdot Al_2O_3$. Spinel may also serve as a sublimation nucleant and is extremely inert chemically. An alloy of two moles of aluminum and one mole of magnesium is commonly used in pyrotechnics because of its ease of ignition. This alloy, stoichiometrically mixed with an oxidizer, should burn to produce a smoke of spinel particles in the form of small spheres or spherical aggregates. Samples of such compositions have been prepared.

6. DESCRIPTION OF PYROTECHNIC REACTIONS

Once the fire has begun, small particles are lifted off the unburned substrata by the evolution of gas and the melting of surface material. These particles, irregular in size and shape, are burned. In materials using silver iodate, oxygen is released and is used to oxidize the fuel. The state of the oxygen is not known.

Depending upon the stoichiometry, temperature and pressure, the silver iodide may break down into free silver and iodine, and the iodine may go to I_2 or I or an admixture thereof. If hydrogen is present in the fuel, some hydrogen iodide is formed unless enough oxygen is present to convert the hydrogen into water. The amount of hydrogen iodide produced by the pressed pyrotechnics is not really very important because the hydrogenrich binder is only a small percentage of the weight. Dependent upon the temperature, such free silver forms molten droplets or silver vapor that partially recombine with the iodine in the extremities of the flame.

Usually, however, the silver iodate simply releases oxygen and melts into little balls of silver iodide of a mass determined by the size of the particle torn off and by the original concentration of silver iodate.

It may be adivseable to increase the proportion of iodine in the reaction by adding some material rich in iodine to ensure the best possible yields of silver iodide. Ammonium iodate may be added for this purpose. Iodine pentoxide (I_2O_5) can be used to advantage in some mixes. Use of elemental iodine is not recommended because it has a tendency to sublime and to react with some organic binders. In general, use of iodine with compounds containing nitrogen or the ammonium radical is not recommended because of the possibility of formation of the extremely sensitive explosive nitrogen triiodide.

7. CONTROL OF TEMPERATURE

The temperature produced by a pyrotechnic reaction may be calculated from simple considerations. The total energy of the reaction can be calculated, and by means of the heat capacity of the products, the temperature can be determined. This must be corrected for external oxidation, radiation and convection.

In general, the hottest reactions occur when stoichiometric mixtures are used. With silver iodide, however, any temperature above 552C can be used for dissemination. The temperature can be controlled while the reaction is still properly oxidized by loading the mixture with an excess of silver iodate or by adding silver iodide. In this manner the temperature can be reduced to as low a value as desired, compatible with satisfactory burning.

8. METHODS OF ASSEMBLY

The mixtures described hertofore can be burned as loose powders. While they may be burned in their powder form, the burning is erratic, and to some extent dangerous. It is preferable to use the mixtures as compact solids. Such a solid can be burned at a uniform rate and can be tailored to use.

In order to compact the materials, the powder is mixed with a binder such as shellac, a nitrocellulose, or styrene cement and a

solvent. The material is then pressed in a mold under several tons per square inch pressure. If the device is to be cased, a paper, micarta, fiber or plastic form is placed in the mold and the material is pressed into that. After being pressed, the solid pieces are cured by gentle heating and, possibly, evacuation to remove solvent. Uncased pieces are generally wrapped in cheesecloth or paper.

The method of ignition depends on the use to which the devices are to be put. Usually one end of a finished grain is painted with a black powder paste or other "first fire," which is in turn ignited by a fuze or an electrical system such as a hot wire. If ignition at high altitude is required, use of a compound that produces a high temperature, very little gas, and exhaust products of a high molecular weight is called for. One such compound is a mixture of varium oxide and magnesium.

9. METHODS OF DISPERSION

Fusee. A number of different fusess of various sizes and delivery rates have been made. The design of the fusee is simple (Fig.1). The materials are contained in a phenolic tube. One end of the tube is sealed with a nomcombustible polyurethane foam plug to protect the mounting rack from high temperatures. The grain is pressed into the tube and the ignition end equipped with a hot wire igniter that sets fire to an ignition pellet consisting of barium oxide and magnesium. A current of about 8 to 12 amp is required to ignite the ignition mixture. The high value of current was selected to avoid accidental ignition by static electricity.

The fusees may be burned on the ground, but the most effective use is on aircraft. Figure 2 shows a supercharged Cessna equipped with a dispensing rack just abaft of the trailing edge of the wing. Figure 3 shows one burning in flight on a rack mounted on the wing strut of a Cessna 206. The unit shown in Fig. 1 burns for 5 min. at an altitude of 20,000 ft. Ignition and burn are reliable to an altitude of 30,000 ft.

Very pistol charges. A handy device for testing small amounts of nucleant is the standard signal pistol called a Very pistol. Use of these is in some states illegal, even for the purposes for which they were intended, and local laws should be checked.

The charge is tailored to fit the pistols, which come in several sizes. Figure 4 shows typical charges. A parachute may be attached to the charge so that it descends slowly; however, it is quite easy to control the duration of burning by boring a hole in the center of the charge, thus making the parachute unnecessary.

The grain shown is ignited by the flash from the expulsion charge. The igtnition end is stepped in an inverted ziggurat. The difficulty inherent in the use of the Very pistol is one of not being

able to fire rapidly. This has been overcome by use of a longer shell, Fig. 5, that fits automatic dispensers, Fig. 2. These units are made with the same molds as the standard fusee and the Very pistol shell but are fired by an electrical cap. They may be dispersed from the standard rack used for fusees. The length of burn is dependent on the length of charge and is made to order. When used with a light plane, the units can be fired aft with the same velocity as the plane and hence fall straight down, the expulsion charge being tailored to the airspeed. A variation that has some appeal to people who want to know exactly where seeding is done consists of a small magnesium oxide smoke puff, produced shortly after ejection, that can be photographed or observed in order to mark the spot.

Roman candles. Dr. B. Vonnegut suggested that we develop a Roman candle such that small charges were ejected at intervals to fall through and seed in depth a supercooled stratus. Two variations were tried, one a loose mixture containing larger pieces of harder slower burning material; the other dispensed up to 36 balls. The expulsive charge was a gassy mixture producing silver iodide; the balls were either a pressed pyrotechnic or were fabricated from a nitrasol mixture or a fluorocarbon mixture. Roman candles are ideal for supercooled fog and cold stratus, but are expensive to manufacture in small quantities.

Firecrackers. Firecrackers are useful for local application of high concentrations of smoke; a simple version, made from a 35-mm film can and ignited by a cherry bomb fuze, is shown in Fig. 6. These explode with a satisfying bang and can be made in any desirable size but are dangerous.

Projectiles. A number of different projectile types were considered and discarded as too dangerous. An all-consumable, ambient pressure burning projectile for a .50-caliber machine gun and a 20-mm gun is under development along the lines suggested by Thomas Stevenson. Previous trials included mortar shells and shotgun cartridges. The projectile system can be made either as continuous burning or as explosive units.

Shells for antiaircraft cannon have been used to disperse silver iodide in the Soviet Union (Sulakvelidze et al., 1965).

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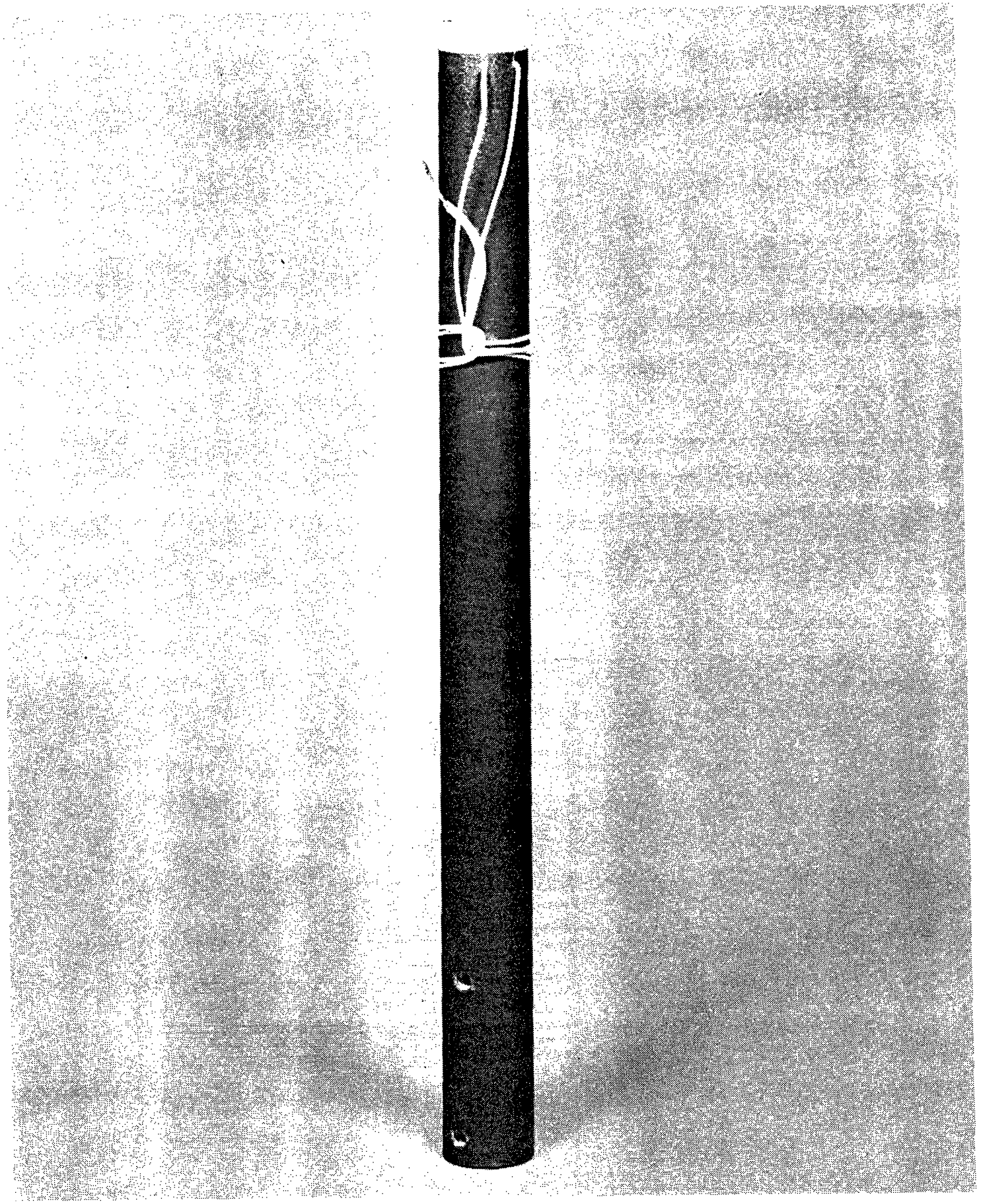

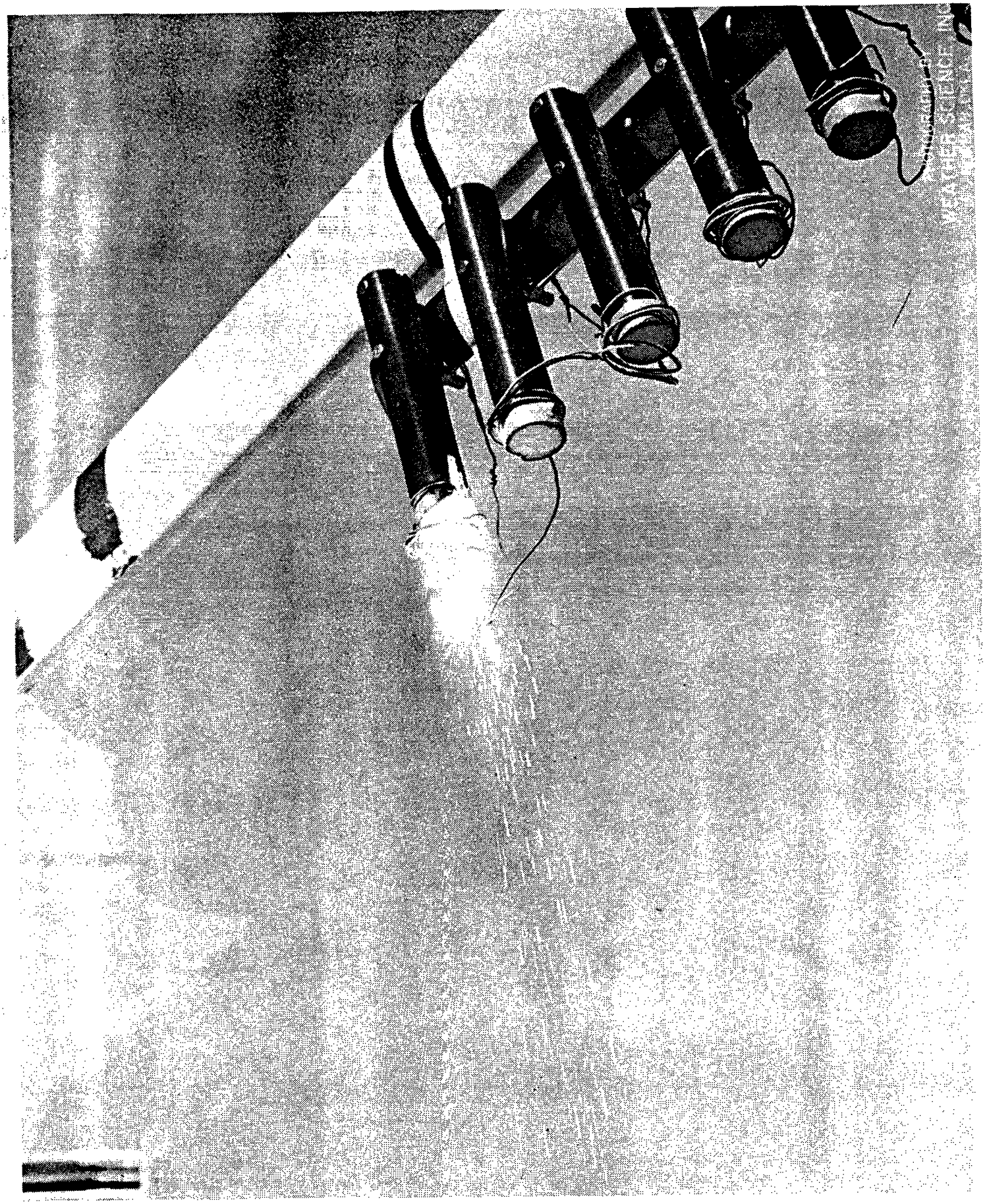

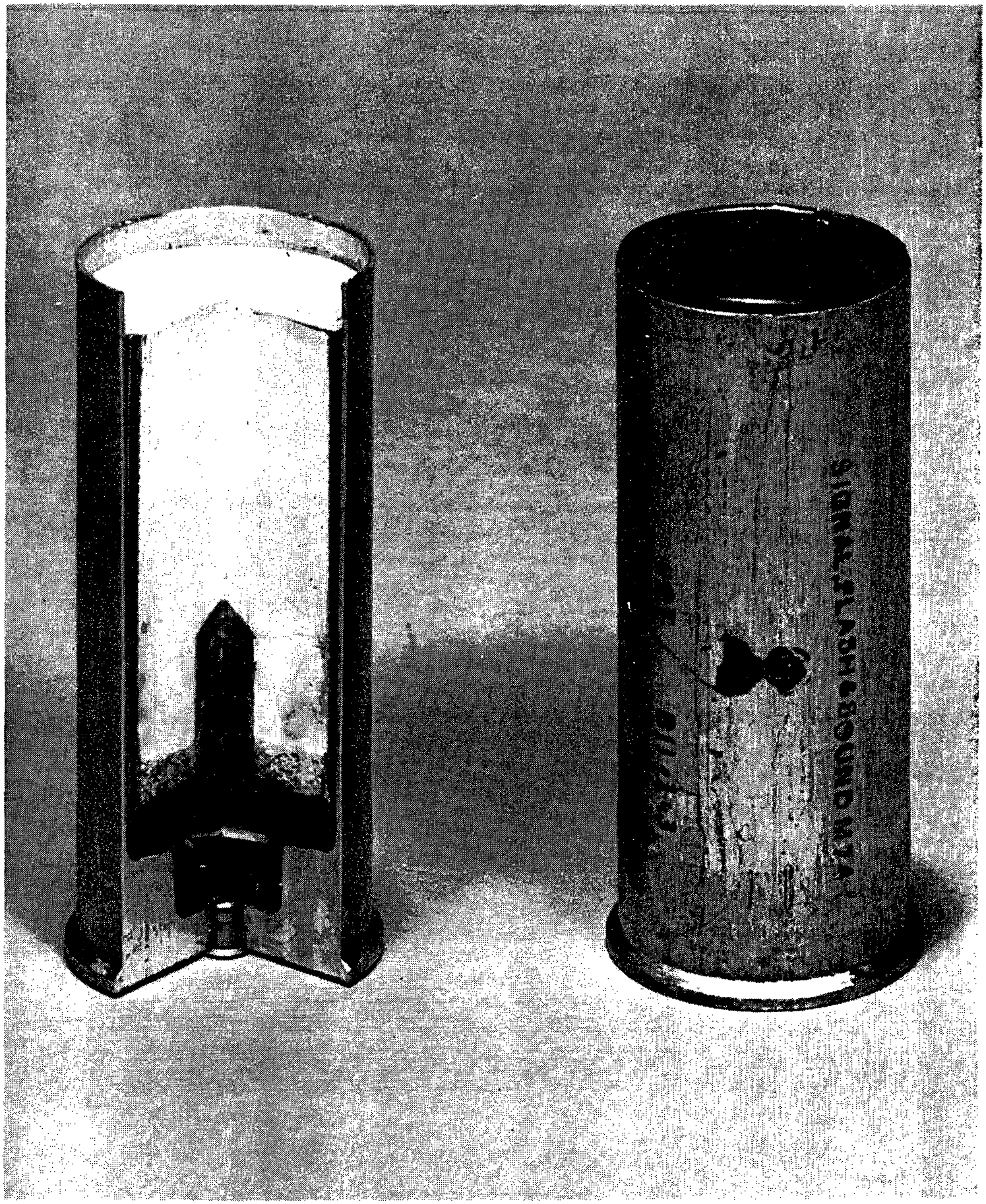
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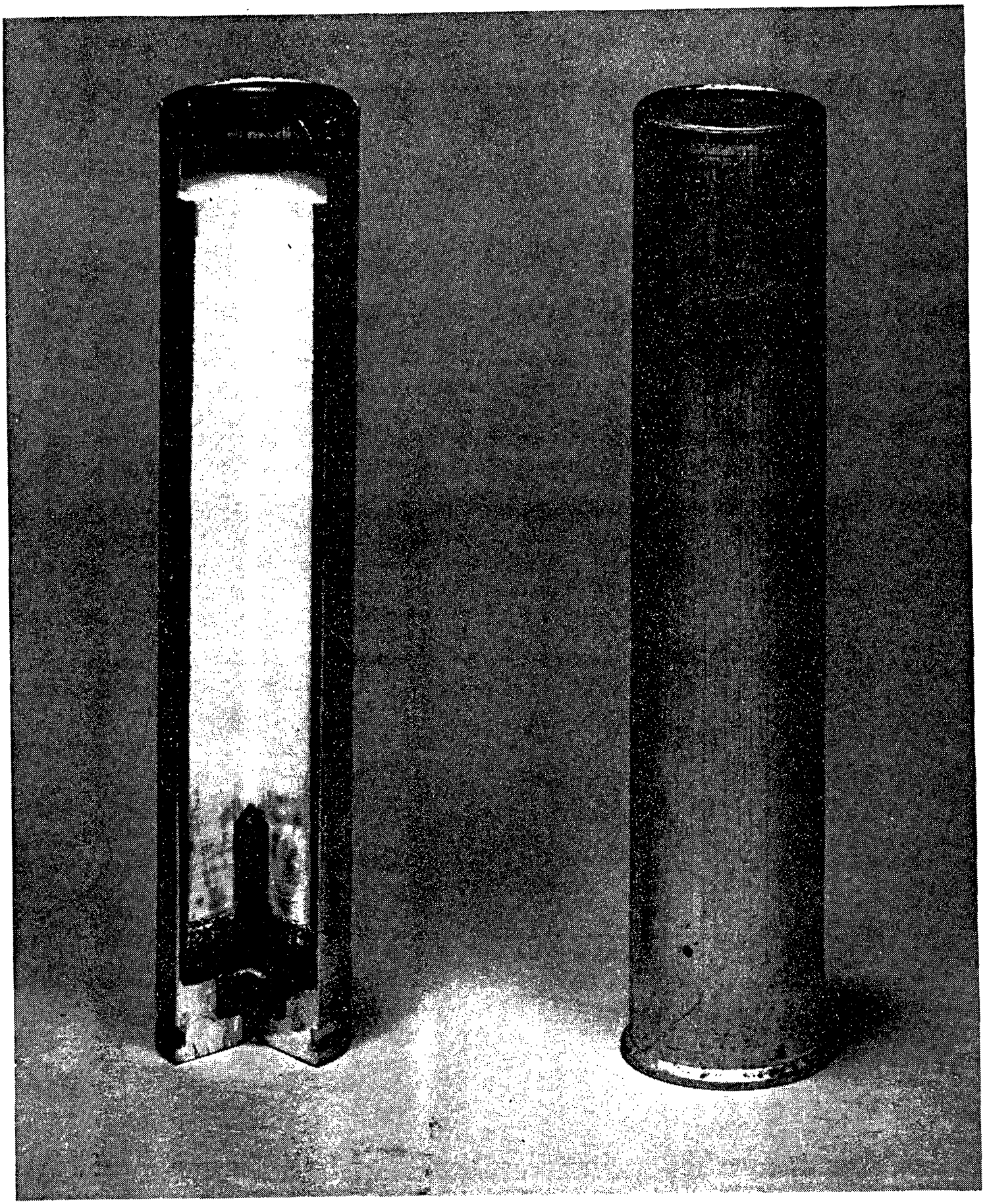

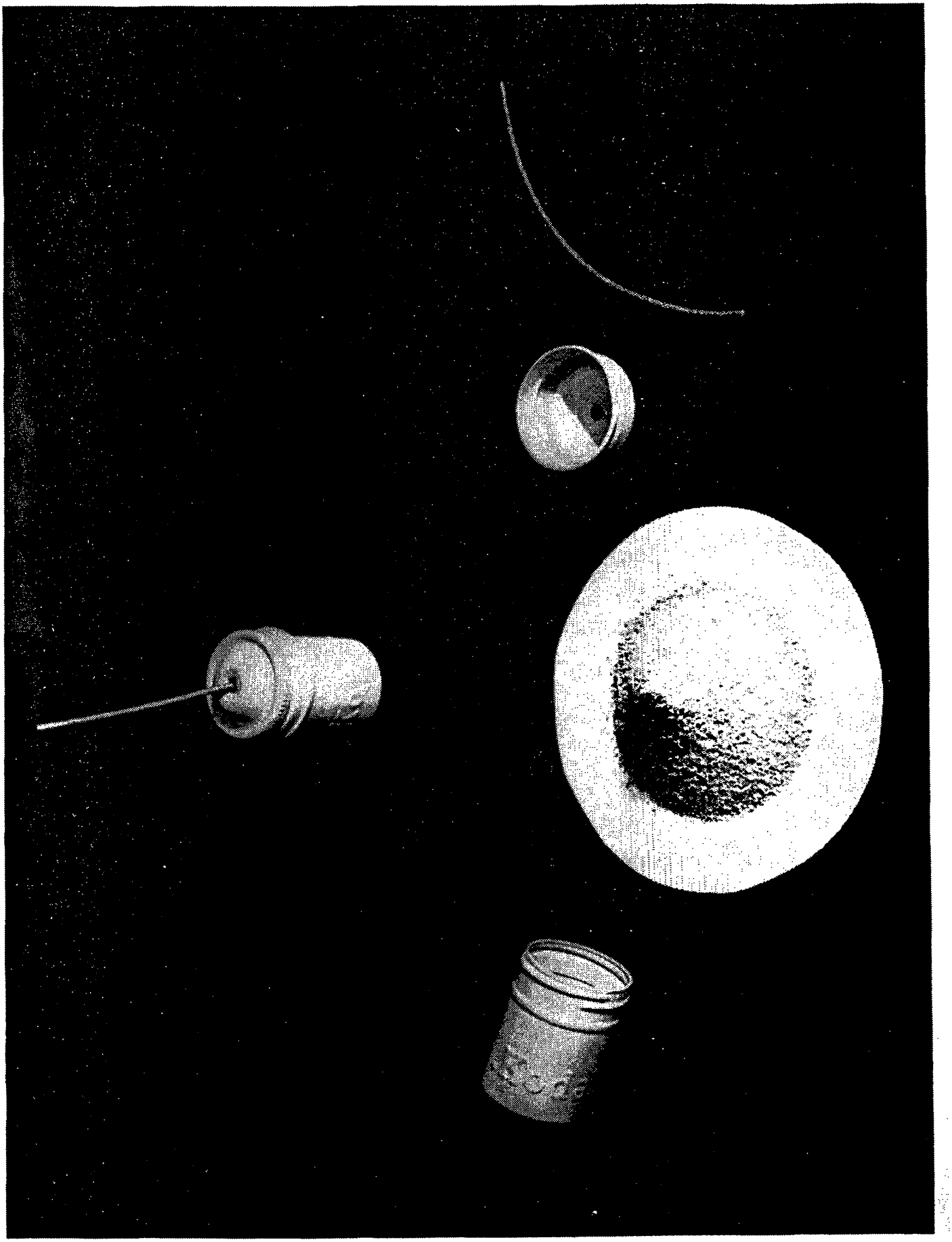

PYROTECHNIC PRODUCTION OF NUCLEANTS FOR CLOUD MODIFICATION

PART III. Propellant Compositions for Generation of Silver Iodide

Ronald F. Vetter, William G. Finnegan, Lohr A. Burkardt, Pierre St.-Amand, H. Sampson and Martin H. Kaufman

Naval Weapons Center, China Lake, Calif.

ABSTRACT

Propellant formulations for production of silver iodide began with the use of $AgIO_3$ and poly(2-methyl-5-vinyl) tetrazole. This yields very pure silver iodide, but is expensive and difficult to use. Plasticized nitrocellulose is an effective binder for use in rocket motors, fuzes, and flares, but is not suited for projectiles. Polybutadiene fuels are excellent for use in rocket motors, but are unsuitable for other uses. Magnesium fluorocarbons are well suited for any use requiring ignition and combustion at high altitudes and in any application requiring physical strength. Polyurethanes are well suited for use as flares, candles, and energetic rocket propellants; double base systems produce exceptionally pure silver iodide and are used for ground burning or applications involving production of precisely reproducible numbers of nuclei such as intercalibration of cold boxes. Extremely high yields are possible from double base materials.

I. INTRODUCTION

Rocket fuels and pyrotechnics are a little-appreciated means of producing chemical compounds. In general, rocket fuels consist of an oxidizer and a binder, which serves as a fuel, that may be burned under pressure. The evolution of large quanitities of gas is a common attribute. We have investigated four families of fuels in some detail: plasticized nitrocelluloses, polybutadienes, flourocarbons, and polyurethanes.

The first studies (1957) at the Naval Weapons Center (NWC) were made using the exotic fuel poly(2-methyl-5-vinyl)tetrazole, C_4H_6N4. The general reaction, balanced to produce both CO and CO_2, is

$$3AgIO_3 + C_4H_6N_4 \longrightarrow 3AgI + 2CO + 2CO_2 + 3H_2O + 2N_2$$

This composition produced copious smoke, the solid particles of which were identified by X-ray and chemical analysis as silver

iodide. The silver iodide proved to be over 95% pure. The only other solid product was metallic silver.

In 1961 the use of pyrotechnically generated silver iodide was suggested to several meteorologists. At the time the only obvious advantages of using pyrotechnics seemed to be the ability to produce large amounts of nucleant and to control the placement because of the numerous delivery techniques possible. The only interest was shown by Dr. Robert H. Simpson, then director of Research for Severe Storms for the U. S. Weather Bureau. We therefore suggested a collaborative effort with the Weather Bureau; NWC was to prepare devices for vertical seeding and to do the seeding with Navy aircraft. The Weather Bureau and the Navy were to observe the storm and measure the results. Joint publication of descriptions and results was to follow.

The seeding devices were required to be dropped at an altitude of 45,000 ft. and to burn until the 20,000-ft. level was reached. The quantities of material were unspecified, but the particle size was supposed to be about 0.1μ in order to ensure freezing at lowest possible levels.

These requirements placed severe restrictions on the seeding system. At that time it was difficult to ignite or burn a propellant reliably at high altitudes because the expansion of the gases brought about adiabatic cooling of the burning surface. Although pressed pyrotechnics were less expensive, the only way to ensure reliability without a long development program was to use a rocket motor in which the material could be burned under pressure. The most obvious way to proceed was to use a nitrocellulose composition. To this end the formulation P-65 was developed.

2. NITRASOL COMPOSITIONS

Silver iodate is only 17% oxygen, and almost any fuel capable of binding it into a sufficiently strong solid would be under-oxidized unless it contained an additional oxidizer or oxygen itself. Hence, a nitrocellulose fuel used with a high-energy plasticizer was, and still is, an ideal choice from a chemical point of view.

The nitrasols produce a very pure silver iodide with almost no other solid products of combustion, unless, of course, aluminum is added. They have been the subject of most of our experimental work in controlling particle size distribution and in preparing exotic nuclei and combinations of nuclei.

Formulations. Numerous formulations have been prepared, some of which are shown in Table 1.

TABLE 1. Nitrasol formulations

Ingredient	CY 1	CY 2	CY 3	CY 4	CY 7	CY 8	CY 9	P65	LPC 1033
Plasticized nitrocellulose	5.0	5.8	5.0	10.0	9.0	6.5	16.2	8.5	39.0
Triethylene glycol dinitrate	10.0	--	10.0	15.0	75.0	--	--	--	25.0
Trimethylolethane trinitrate	--	11.6	--	--	--	--	--	--	--
Wax	--	--	2.0	--	0.2	0.2	0.6	--	--
Pentaerythritol trinitrate	--	--	--	--	15.5	12.0	30.0	21.0	--
Fibruous nitrocellulose	--	--	--	--	1.0	1.0	2.5	--	--
Resorcinol	--	--	--	--	0.2	0.2	0.6	0.5	1.0
Lecithin	--	--	--	--	--	--	--	--	--
Aluminum	--	--	--	--	--	5.0	12.5	5.0	5.0
Silver iodate	85.0	82.5	83.0	75.0	--	75.0	--	65.0	30.0
Lead iodate	--	--	--	--	--	--	37.5	--	--

These formulations are made by blending the binder system of plastisol nitrocellulose with a liquid, nitrate ester plasticizer in an evacuated mixer at room temperature. The other ingredients are added and mixing is continued until a homogeneous state is reached. The material is then poured into the desired container and cured by heating in an oven. The viscosity of the mix must be low enough to stir and high enough to prevent settling of the solid ingredients. One problem is that it is often difficult to be able to mix as much solid material as is desirable into the nitrasol.

Curing times and temperatures are variable and depend upon the particular batch of nitrocellulose and the nitrate ester. Curing temperatures range from 50 to 80C. Some formulations, such as P-65, indicate a tendency toward spontaneous decomposition at about 75C, so that a fire or detonation during curing is always a possibility. The introduction of magnesium powder into nitrasols usually results in a greatly increased burning rate and explosion; hence, magnesium should not be used with nitrasols unless such behavior is desired. Nitrasol formulations are hazardous to manufacture and are not suitable for "do it yourself" projects. They are safe to use once they are made, however, and the foregoing caveat should not be taken to indicate that they are unsuitable for use in devices for weather modification.

Deliberate detonation of nitrasol formulations containing silver iodate results in the production of few silver iodide ice nuclei; usually the silver iodate is scattered about the area as dust, along with unburned bits of the formulation.

Method of use. The nitrasols are best suited as casting fuels in rocket motors burned under pressure. They serve well as fusees and flares burned at ambient pressures and can be used up to about 20,000 ft. Fusees using P-65 were used as early as 1961 to nucleate the Sierra Wave cloud. The material is not well suited for use in Very pistols and other projectiles because ignition is difficult and the material is too elastic.

The materials can be made to burn over a wide temperature so that control of the temperature is exact. This permits the manufacture of units that will burn at a temperature low enough to melt and disperse the silver iodide as submicron particles but not high enough to decompose or vaporize it. The nitrasols are ideally suited for experimental work to develop new concepts in nucleation.

3. POLYBUTADIENE

The polybutadiene formulations resemble rubber erasers in appearance. They cannot be detonated by normal means, and they are reasonably inexpensive and are safer than the nitrasol compounds. Several satisfactory propellant compositions for the dissemination of silver iodide were developed.

Formulations. A large number of formulations were investigated using a computer to find the best possible mixture for use in generating silver iodide. The basic chemistry is shown in the unbalanced equation:

$$AgIO_3 + C_4H_6 + Al \longrightarrow AgI + Ag + I_2 + CO_2 + H + H_2 + HI$$

$$+ C + Al_2O_3 \longrightarrow$$

$$AgI + H_2O + CO_2 + CO + HI + I + Al_2O_3$$

The C_4H_6 $_n$ represents the polybutadiene. Tables 2 and 3 show several formulations and their physical properties. Table 4 shows the plasma compounds during burning.

TABLE 2. Polybutadiene formulations

Ingredient	Percent by weight of ingredient for indicated formulation					
	CY 6	CY 12	CY 19	CY 20	CY 21	CY 35
Silver iodate	85.0	90.0	87.5	91.0	89.0	80.0
TMETN*	3.5	2.5	2.5	2.5	2.5	3.5
Polybutadiene binder	11.5	6.0	6.5	6.5	7.0	11.5
Aluminum	0.0	1.5	3.5	0.0	1.5	5.0

*TMETN = Trimethylolethane trinitrate, $C_5H_9N_3O_9$.

TABLE 3. Physical properties of polybutadiene formulations

	CY 6	CY 12	CY 19	CY 20	CY 21
Heat of exp. (cal/g)	354.0	497.0	514.0	407.0	438.0
Density (g/cc)	3.03	4.02	4.0	4.09	3.95
Total weight AgI produced (%)	70.8	74.6	72.6	75.6	73.9
Tensile strength (lb/in^2)	30.0	105.0	105.0	70.0	52.0
Modulus	240.0	863.0	1030.0	480.0	2000.0
Burning rate (in/sec)					
at 100 psig	0.068	0.125	0.121	0.109	0.107
at 535 psig	0.150	0.245	0.223	0.191	0.192
at 1065 psig	0.230	0.364	0.277	0.255	0.253

TABLE 4. Calculated plasma species before recombination

Plasma Species	Mole per cent of plasma species for indicated formulation			
	CY 12	CY 20	CY 21	CY 35
VAPOR				
HI	8.88	20.51	12.68	5.18
H	--	--	--	0.03
H_2	4.48	6.24	7.81	28.67
I_2	1.01	1.50	1.05	0.07
Ag	--	--	0.00	0.67
H_2O	13.83	7.90	10.49	0.01
CO_2	18.82	31.49	15.09	0.01
I	11.50	0.08	6.18	5.69
CO	16.09	6.73	22.90	35.37
N_2	1.03	1.08	0.98	0.95
CH_4	0.00	0.51	0.00	0.01
AlI	--	--	--	0.15
AlI_3	--	--	--	1.56
LIQUID				
Ag	22.38	23.60	20.97	12.35
SOLID				
Al_2O_3	1.96	0.00	1.85	3.42
C	--	--	--	5.87
Exhaust temp. (^oK)	1516	820	1371	1700

Once again it must be remembered that these results are theoretical and are based on thermochemical data that are not entirely correct. The main sources of concern are uncertainity in the data for silver iodate and silver iodide. The errors will be mainly in making the dissociation of silver iodide appear more prominent than it really is.

Polybutadiene has a high oxygen requirement for complete combustion, and silver iodide is a poor oxidizer. It is impossible to use enough silver iodate to completely oxidize the polybutadiene and still have enough polybutadiene to bind the ingredients together in a mechanically strong matrix. The heat of combustion of polybutadiene is not great enough to vaporize all the silver iodide and so aluminum is added to the formulations to raise the heat of combustion and the flame temperature. The presence of aluminum presents an additional oxygen demand which could only be met by adding another oxidizer or a high-energy explosive plasticizer.

As can be seen from Table 4, combustion is not complete within the rocket motor. For example, carbon monoxide is about as abundant as carbon dioxide, and molecular hydrogen is still present and in the case of CY 35 is more abundant than water. Solid carbon is present in the exhaust gas, but this is not important for our purposes.

The smoke from CY 20 is purplish because it contains excess iodine caused by the retention of silver in the motor case. The smoke of CY 21 is a brownish orange in the middle of the plume and whitish gray with purple overtones near the edges. The smoke from CY 35 is much darker than the smoke from the other formulations because of the free carbon present.

Choice of formulation for seeding. Compositions of polybutadiene and silver iodate for ground seeding have been elavorated, but because of the underoxidized state of the formulation they burn poorly at ambient pressure and release a fair amount of iodine. Pressed pyrotechnics, nitrasol formulations, and flourocarbon compositions have been more appropriate for this purpose; however, if an additional oxidizer is added, stoichiometric burning is attained and the material is satisfactory for flares and fusees.

The true forte of the polybutadiene compositions is as a binder in propellants burned under pressure. A much higher proportion of solids is possible than with the nitrasols. Good safety characteristics, storage stability, and even burning of the compounds are very advantageous.

Of the compounds in Table 1, all except CY 20 serve well as a fuel to produce silver iodide in an enclosed rocket motor. The CY 20 does not have a high enough combustion temperature, and not all the silver iodide and silver is removed from the motor case. Of the others, CY 21 is the most suitable, having good physical properties and only a slight change of burning rate with pressure. CY 21 was used in Alecto

and Cyclops II until 1966, when CY 21M was developed. The compositional changes are slight.

CY 35 was elaborated to detect the changes brought about in the nucleation effectiveness by operating the motors at a higher temperature and exhaust velocity. The nucleation efficiency of the CY 35 smoke, as shown by a mixing-type cloud chamber, is better than that of CY 21 at both warmer and colder temperatures but less at intermediate temperatures.

Analysis of combustion products. The solid particles from the smoke of an Alecto CY 21 were analyzed; results are shown in Table 5.

TABLE 5. Results of analysis of smoke from an Alecto CY 21

Ingredient	Content, %
Silver iodide	76.4
Potassium iodide	3.0
Metallic silver	8.5
$R_2O_3(Al_2O_3, Fe_2O_3, Si_2O_3)$	8.5
Unidentified	3.6

Potassium was present as an impurity in the silver iodate. Some nitrogen trioxide and ammonia were also present in the silver iodate. These compounds are practically impossible to remove without a great increase in cost. The presence of free silver is due in part to the escape of iodine and in part to the presence of as much as 10% free silver and some silver iodide in the silver iodate.

Considering that 24% of the original composition would be converted to volatile materials, the conversion rate for silver iodate to silver iodide is almost 100% within the limits of error on the analysis. The large amounts of oxides are due in part to material picked up from the heat liner of the container and from the container itself.

The particle size as determined by X-ray diffraction is about 200 to 400A. The nucleation efficiency of silver iodide produced from the polybutadiene compositions, notably CY 21, is equal to or better than that from any other means of production as will be discussed in a later section of this series. When burned in Alecto at a pressure of about 350 psi the CY 21 produces about 10^{15} nuclei per gram of silver iodide at -20C and 2×10^{11} nuclei per gram at -5C as measured in a mixing-type cloud chamber. This latter figure is at least ten orders of magnitude better than an acetone burner at that temperature.

An improvement could be effected in the nucleation effectiveness

of the polybutadiene and other compositions by using less silver iodate, an additional oxidizer, and an auxiliary source of iodine so that the recombination of silver with iodine would be more complete. New formulations using iodine pentoxide as an additive are being investigated.

4. MAGNESIUM FLUOROCARBONS

The reaction involved in magnesium-Teflon fuels is different from those of the preceding sections. The others used the iodate of silver or lead to oxidize a binder and a metal fuel. The magnesium-Teflon formulations do not rely on oxygen but instead use a reaction between magnesium and flourine,

$$C_2F_4 + 2Mg \longrightarrow 2MgF_2 + 2C$$

This reaction yields a good deal of heat and produces little gas. The iodides of silver or lead could be used instead of the iodates because the reaction is energetic enough to vaporize and disseminate the silver iodide without the addition of oxygen. The addition of silver iodate leads to the combustion of some of the carbon and the production of magnesium oxide.

Formulations. Examples of formulations tried are shown in Table 6; physical properties are shown in Table 7.

TABLE 6. Magnesium flourocarbon formulations

Ingredient	Percent by weight of ingredient for indicated formulation			
	CY 10	CY 14	CY 16	CY 17
Silver iodate	70.00	--	80.00	80.00
Lead iodate	--	65.00	--	--
Magnesium	10.00	10.00	8.00	8.00
Teflon	14.00	9.00	5.00	5.00
Viton	5.00	15.00	6.00	6.00
Carbon black	1.00	1.00	1.00	1.00

TABLE 7. Physical properties of magnesium fluorocarbon formulations.

	CY 10	CY 14	CY 16	CY 17
Heat of exp. (cal/g)	903	798	737	790
Exhaust temp. (^{o}K)	--	--	2137	--
Density (g/cc)	3.50	3.43	3.83	3.89
Tensile strength (lb/in^2)	972	1203	640	672
Modulus	17300	13030	4843	7482
Burning rate (in/sec)				
at 100 psig	0.068	0.034	0.065	0.069
at 535 psig	0.137	0.081	0.155	0.145
at 1065 psig	0.218	0.122	0.238	0.222

Polytetrafluoroethylene (Teflon) is a heavy, relatively hard polymer, $(C_2F_4)_n$. Powdered Teflon is mixed with the magnesium and silver or lead iodate and with Viton, an elastomer containing hydrogen, flourine, and carbon dissolved in a solvent. The mixture is blended, dried, and then extruded through a die. The solvent is evaporated before extrusion and plays no further part in the reaction. Considerable equipment is needed to make and extrude the materials, and the safety considerations are important, for, as with most of these compounds, it is almost impossible to put out a fire once it begins to burn.

Exhaust products. The smoke from the magnesium flourocarbons is usually a bright yellow in the center of the plume with bluish white smoke on the extremities. The solid exhaust products are silver iodide, magnesium oxide, and magnesium flouride.

Magnesium flouride is a colorless solid with a density of 3.0, and a molecular weight of 62.31. It is crystallized in the tetragonal system and has a structure similar to that of rutile. It occurs in nature as the rare mineral Sellaite. It melts at 1266C and boils at 2239C, and its solubility in cold water is 8×10^{-5} g/cm^3. Fukuta (1958, p. 22) gives -7.9C as the activation temperature for magnesium flouride and -9.3C for magnesium oxide; hence these two products could be expected to add additional useful nuclei over and above those produced by silver iodide.

It is also possible that some flourides of silver, silver flouride, silver diflouride, and disilver flouride might form. Of these compounds, silver flouride is deliquescent and disilver flouride and silver diflouride decompose in cold water. Production of these compounds is probably minor because the formation of magnesium flouride is strongly favored, and any excess of magnesium in the reaction will minimize the formation of silver flourides.

Method of use. The magnesium fluorocarbon series is well suited for any application requiring a physically strong material. The ease of extrusion makes it feasible to produce long strands suitable for ground burning, pellets for Roman candles, Very pistol shell, fusees, and almost any other form of pyrotechnic dissemination. The material is hard to ignite, and once made is satisfactory from a safety standpoint. It will burn well without confinement regardless of altitude. This sytem is well suited for further development.

5. POLYURETHANE

Sample batches of polyurethane-bound cloud-seeding compound called Urethane Cyclops D and CY 52, consisting of the ingredients shown in Table 8, were procured.

TABLE 8. Composition of UCYCD and CY 52

Ingredient	Percent by weight of ingredient for indicated formulation	
	UCYCD	CY 52
Castor oil	4.1	6.3
Dipropylene glycol	1.5	2.3
Toluene diisocyanate	2.8	4.2
Trimethylolethane trinitrate	4.2	6.4
Lecithin	0.5	0.8
Silver iodate	87.0	77.0
Aluminum	0.0	3.0

The formulation for UCYDC is stoichiometrically balanced to carbon monoxide and uses no metal fuels or other oxidants. The only solid product of the smoke is silver iodide, with, of course, any alkali iodides present in the original silver iodate.

The material is prepared by mixing the ingredients of the binder in the order shown and then adding finely ground silver iodate. The material is cured for 2 to 4 days at an elevated temperature. The physical properties are given in Table 9.

TABLE 9. Physical properties of UCYCD

Maximum tensile strength (psi)	57
Elongation at rupture (%)	20
Modulus	800
Heat of explosion (cal/g)	416
Burning rate (in/sec)	
at 100 psi	0.085
at 1000 psi	0.250
Density (g/cc)	3.71

Without aluminum the formulation is adequately oxidized to burn well, ignites easily, and is energetic enough to serve as a rocket propellant. One 5-inch cylindrical motor burned at 400 psi produced a 200-lb thrust, the specific impulse was 90 lb-sec/lb, and the exhaust velocity was about 2100 ft/sec. The smoke from UCYCD, burned at ambient pressure, is a beautiful yellow in dense smokes and bluish white in more dilute smokes.

The addition of aluminum changes the temperature and decreases the state of oxidation by preempting the available oxygen. The compound when burned without aluminum produces more uniform particle sizes than when burned with aluminum. When aluminum is used, more large particles are produced.

Method of use. The materials can be used as pressure-burning fuels in self-propelled rockets or as fusees or candles in devices burned at ambient pressure up to, perhaps 20,000 ft. This family is very cheap, insensitive, effective, should be quite useful, and deserves a good deal more development. The chief improvement could, as in the polybutadiene family, be a slight addition of another oxidizer containing excess iodine.

6. DOUBLE-BASED PROPELLANT SYSTEMS

A limited amount of material for use in the standardization of nuclei-testing devices and cloud chambers has been produced using a double-based composition consisting of a mixture of nitroglycerine and nitrocellulose. This material is blended with less than 15% of silver iodide or iodate and is extruded through a die under high pressure to form a strand, usually one or two millimeters in diameter. The material has a very uniform burning rate and can be cut into whatever lengths necessary to give a predetermined amount of silver iodide. The yield of nuclei from this system is quite high, approaching 2×10^{13} nuclei per gram effective at -5^{0} C. The material is safe when

used in small-diameter strands but is not suitable for operational use because of the difficulty in keeping it burning at high altitude and because of the possibility of a self-propagating explosion when it is used in larger diameters. The only use made of this material to date is in the intercomparison of nuclei-counting devices.

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PYROTECHNIC PRODUCTION OF NUCLEANTS FOR CLOUD MODIFICATION

PART IV. Compositional Effects on Ice Nuclei Activity

Lohr A. Burkardt, William G. Finnegan, F. Kirk Odencrantz
and Pierre St. Amand

Research Department
Naval Weapons Center, China Lake, Calif.

ABSTRACT

Fine particle dispensions of silver iodide and mixtures and complexes of silver iodide with alkali iodides can be generated by pyrotechnic combustion of compositions containing energetic oxygenated precursors of the metal iodides. The solid products of combustion of such pyrotechnics have been characterized by wet chemical and X-ray diffraction analysis and by comparison of data obtained on synthetic samples.

The chemical complexes of silver iodide with the alkali metal iodides are active ice nuclei although their physical and chemical properties differ from those of silver iodide.

Ice nuclei activity studies of simple and complex nuclei generated by pyrotechnics have been made. Nuclei from pyrotechnics burned in a 24 m^3 cloud chamber in the presence of the supercooled fog, show enhanced activities at warm temperatures compared to activities obtained by nuclei dilution and injection techniques.

1. INTRODUCTION

The pyrotechnic generation of artificial ice nuclei, using oxidizing species as nuclei precursors, is a novel process that makes possible the preparation of a wide range of nuclei having discrete chemical compositions and physical properties.

Metal iodates are used as added ingredients in energetic pyrotechnic formulations. Upon combustion, the iodates are reduced to iodides which appear as solid products after cooling. For example:

$$2\ AgIO_3 \rightarrow 2\ AgI + 3\ O_2$$

When mixtures of silver iodate and alkali iodates are incorporated in the pyrotechnic, the solid products of combustion may appear as simple mixtures, complexes or complex hydrates depending on the molecular ratio and the physical and chemical properties of the products, the rate of

quench to ambient temperature and the length of time the products are exposed to atmospheric and pyrotechnically produced water vapor.

Silver iodide ice nuclei activity spectra have been determined for a wide variety of pyrotechnic formulations incorporating silver iodate. (Davis and Steele, 1968). The majority of these formulations generate solid products composed of mixtures of silver iodide and inorganic oxides, such as aluminum oxide, magnesium oxide, and potassium oxide (or hydroxide) from metals or added oxidizers in the pyrotechnic formulation. The ice nuclei activities of these oxides or their influence on the ice nuclei activity of the silver iodide have not been characterized. An effort has now been made to generate silver iodide containing a minimum of impurities to characterize the generation process and to establish the ice nuclei characteristics of the product as a function of silver iodate purity and concentration in the pyrotechnic.

Silver iodide is generally considered to compose the active ice nuclei obtained by combustion of acetone solutions of silver iodide and an alkali iodide. The chemical and physical properties of the actual products are, however, markedly different than those of silver iodide (de Pena and Caimi, 1967). The interesting possibility exists, therefore, that the ice nuclei activity of those materials may be due, at least in part, to chemical complexes of silver iodide and alkali iodides. Such complexes have been described in the chemical literature (see for example, Mellor, 1946).

2. ALKALI IODIDE-SILVER IODIDE COMPLEXES

Table 1 lists most of the alkali iodide-silver iodide complexes reported in the literature and those complexes studied in this laboratory for which X-ray diffraction evidence indicating their existence has been obtained. Of the five systems of alkali iodide and silver iodide indicated in Table 1, three systems, cesium iodide-silver iodide, potassium iodide-silver iodide and sodium iodide-silver iodide, have been studied with respect to complex formation.

Cesium iodide is reported in the literature to form three complexes: CsI-AgI, CsI-2AgI and 2CsI-AgI by fusion of mixtures of the components. In this laboratory, evidence (X-ray diffraction) has been found for four crystal modifications of the equimolar composition, CsI-AgI. The conditions governing the formation of these polymorphic modifications have not been clearly established as yet. Two of the forms may be crystallographically similar as they tend to co-crystallize from melts or acetone solution. The formation of one of these two forms is enhanced by the presence of an excess of cesium iodide. For example, the fusion of a mixture having the molar ratio 2CsI-AgI, upon cooling, leads to a mixture of this latter polymorph and cesium iodide. It may also be found in a 1:1 mixture of cesium iodide and silver iodide which has been held in contact with an acetone solution of these salts. The latter conditions at times lead to the formation of the third crystal modification. The fourth crystal modification of CsI-AgI is obtained by very rapid quenching of melts

having the 1:1 ratio. This has been done in the laboratory by melting the mixture in a capillary tube and rapidly removing it from the heat source. This form represents a high temperature modification which is unstable at lower temperatures but is retained in a metastable state by virtue of the very rapid quench. Such high temperature modifications are of interest in connection with the pyrogenisis of ice nuclei for weather modification studies because the nuclei so formed tend to be rapidly quenched.

No evidence for the existence of a stable complex 2CsI-AgI has been found in the studies to date. As pointed out earlier, fusion of a mixture of this composition results in the formation of CsI-AgI and CsI. Rapid quench of a melt of 2CsI-AgI does, however, yield a metastable complex.

The behavior of cesium iodide-silver iodide systems with water differs from those of lithium iodide-silver iodide, sodium iodide-silver iodide and potassium iodide-silver iodide systems. With the latter systems the addition of water results in solution of the solids. With continued addition of water, a dilution is reached at which silver iodide precipitates from the solution. The cesium iodide-silver iodide system behaves similarly except that, instead of silver iodide, the complex CsI-2AgI is precipitated.

Complexes of rubidium iodide and silver iodide, described in the literature, include 2:1, 1:1, 1:2, and 1:3 mole ratio products. A half mole hydrate of the 1:1 molar complex has been reported.

Potassium iodide and silver iodide have been reported to form complexes with molar ratios (KI:AgI) of 1:1, 1:3, 1:4, and 2:1. Hydrates of the complexes having molar ratios 1:1 and 3:1 have been reported. The X-ray diffraction patterns of the potassium iodide-silver iodide complexes are quite complex and tend to show considerable similarity to each other; these factors complicate the analysis of the data. An initial survey indicates complexes having the molar ratios (KI:AgI) of 1:1, 2:1, 3:1, 3:2, 2:3 and hydrates of the ratios 1:1 and 2:1. Evidence for three modifications of the 2:3 molar ratio complex, which are dependent on the mode of formation, has been found. A metastable modification of the complex 3KI-2AgI is formed by the rapid quench technique. A number of efforts to prepare the reported complex KI-4AgI (Bradley and Greene, 1966) have failed.

Sodium iodide and silver iodide have been reported to form complexes with molar ratios (NaI:AgI) of 1:1 and 1:2 and a hydrate of the 1:1 complex, NaI-AgI-3.5 H_2O. Efforts in this laboratory to prepare stable unsolvated sodium iodide-silver iodide complexes have failed. Results in this laboratory indicate the hydrated equimolar complex is a tri-hydrate rather than the 3.5 mole hydrate; but the small weight difference between NaI-AgI-3H_2O and NaI-AgI-3.5 H_2O and the marked hygroscopicity of this material makes a precise determination difficult. Evidence has been obtained that complex formation is preceded by solvation of the sodium iodide. In the presence of

water, sodium iodide appears to react with water to form the dihydrate (NaI-2 H_2O) which reacts with silver iodide and additional water to form the complex. Some X-ray diffraction evidence has been obtained for the existence of metastable modifications of the complexes NaI-AgI and NaI-2AgI.

Lithium oxide is reported to form a 1:2 mole ratio complex with silver iodide. While this complex has not been studied, the extremely high heat of hydration of lithium iodide suggests that hydrated complexes are likely.

Laboratory investigations are in progress to fully evaluate the alkali iodide-silver iodide complexes. Determinations of the heats of formation, hydration, solution and dilution of the known complexes of interest may contribute to the understanding of behavior of these ice nuclei at low degrees of supercooling.

3. PYROTECHNIC FORMULATIONS AND ANALYSIS OF COMBUSTION PRODUCTS

To investigate the chemical, physical and, in particular, the ice nucleating characteristics of silver iodide and of alkali iodide-silver iodide complexes, pyrotechnic compositions were formulated incorporating either silver iodate alone or mixtures of the alkali iodates and silver iodate in discrete molar ratios. The concentration of silver iodate in each formulation was 5% by weight except where high molar ratios of alkali iodate necessitated reduction of the silver iodate concentration to keep the total silver iodate and alkali iodate content to 50% of the weight of the composition. The formulations contained 50% nitrocellulose and varying percentages of ammonium nitrate depending on the weight percentage of the alkali iodate. Silver iodate, commonly prepared by admixture of aqueous solutions of silver nitrate and an alkali iodate, is an impalpably fine, submicron size powder which tends to absorb minor quantities of co-reactants and co-products during precipitation. Unfortunately, the universal tendency is to use the cheaper reactant (alkali iodate) in slight excess to prevent loss of the more valuable silver nitrate. Silver iodate is thus commonly contaminated with alkali iodate. Recrystallization of the silver iodate by evaporation of aqueous ammonium hydroxide solutions gives a larger particle size product more easily incorporated into pyrotechnic formulations, but this treatment does not result in significant purification. A much purer product can be prepared by reaction of reagent grades of silver oxide and iodic acid in aqueous solution but trace contamination by alkali from glass equipment is still possible.

Three grades of silver iodate were used in the 5% silver iodate concentration formulations to study the effects of alkali metal salt contamination and silver iodate particle size on the ice nuclei activity of the resultant silver iodide. These grades of silver iodate and their sources were: (1) commercial recrystallized, 97% purity, (analysis showed 3% potassium iodate), Tennent Chemical Co., Trenton,

N. J., (2) NWC laboratory preparation, $AgNO_3+KIO_3$, unrecrystallized, estimated purity 99% by X-ray diffraction analysis, (3) NWC laboratory preparation, $Ag_2O+2HIO_3$, unrecrystallized, estimated purity > 99% by X-ray diffraction analysis. Some of the products of combustion of the complex nuclei pyrotechnics were collected characterized by wet chemical and X-ray diffraction analysis and the results compared with the data available on known complexes, or determined on synthetic samples. Gross analysis of the solid products of combustion indicated their compositions to consist of silver iodide, alkali iodide and trace quantities of free silver. X-ray diffraction patterns of the products indicated that complex situations existed. This latter study is incomplete; the extreme hygroscopicity of many of the products makes collection and analysis difficult, since water vapor is a product of combustion. A pyrotechnic incorporating 5% of the purest silver iodate and generating only silver iodide was also sampled: Silver iodide was shown to be the only solid products of combustion by X-ray powder pattern analysis. The crystal structure of the silver iodide is either a mixture of the face centered cubic and hexagonal crystal polymorphs or a previously undescribed polymorph with characteristics of each. Characterization of this product is still in progress.

4. ICE NUCLEI ACTIVITY TESTING

Ice nuclei activity spectra were measured in the NWC 24 m^3 cloud chamber by burning small samples of pyrotechnic compositions directly in the presence of supercooled fog over the temperature range 0 to -20C. By this technique, the ice nuclei properties of the solid products of combustion are determined under conditions of actual in-cloud generation.

The initial tests utilized formulations generating silver iodide and complexes of silver iodide with cesium iodide, rubidium iodide, sodium iodide or lithium iodide in 1:1.5 molar ratios. For comparison, pyrotechnic formulations containing 1, 5, 10 and 15% by weight of silver iodate, but no alkali iodate, were submitted for ice nuclei activity spectra measurements to the Colorado State University cloud chamber facility (Steele and Krebs, 1967).

Fig. 1 shows the ice nuclei activity spectra for the initial series of formulations, as determined in the NWC chamber. Fig. 2 shows the data obtained from the Colorado State University cloud chamber for the silver iodide generators. The curves shown are least squares fits to the data. The silver iodide generating formulations using the three grades of silver iodate did not give discernably different ice nuclei activity data and are not differentiated in Fig. 1. The spectrum for complex cesium iodide-silver iodide nuclei does not show enhanced activity over that for silver iodide alone. Nevertheless, sufficient cesium iodide is present in the nuclei to complex the silver iodide completely. The rubidium iodide-silver iodide system shows slightly enhanced activity over that of silver iodide. The sodium iodide-silver iodide, potassium iodide-silver iodide and lithium

iodide-silver iodide nuclei all show greatly enhanced activity over that for silver iodide.

The ice nuclei activity data of the silver iodide from the 5% silver iodate pyrotechnic as determined in the NWC chamber are markedly different from the data obtained by the Colorado State University facility. Not only are the activities at warmer temperatures significantly higher ($\sim 2 \times 10^{12}$/g at -5C vs effectivity 0 at -5C), but the threshold temperature value of ~0C measured in the NWC chamber is much higher than the commonly accepted value of ~-4C. It is to be noted that the supercooled fog (~ 3 g/m^3 liquid water content) generated in the NWC chamber is unstable and evaporates in 5-8 minutes if not nucleated. The pyrotechnic sample is burned at one point in the center of the chamber and very small samples (< 10 mg) are necessary to avoid obvious over-nucleation when determinations are made at temperatures below -10C. Since the experimental techniques employed in each facility differ markedly, interpretation of these results by simple data comparison is difficult, if not impossible at this time. A tentative analysis of the techniques and results suggests that contact nucleation of droplets predominates in the NWC chamber.

The data shown in Fig 1. suggested that the potassium iodide-silver iodide series would be of more immediate interest to study in detail since this particular activity spectrum showed the highest activity at warmer temperatures. Formulations calculated to yield complex nuclei with potassium iodide-silver iodide molar ratios of 1:3, 1:1, 2:1, 3:1, 12:1 and 65:1, were then made and their ice nuclei activity spectra determined. These spectra are shown in Fig. 3. The ice nuclei activity at the warmer temperatures rises markedly over that for silver iodide alone when sufficient potassium iodide is present to completely complex the silver iodide. The activity curves for the 1:1, 1:2, 1:3 and 1:12 mole ratio KI-AgI complexes are essentially superimposeable over the entire temperature range, despite the wide variation in potassium iodide content. Warmer temperature activity then falls with further potassium iodide dilution. Although less effective at warmer temperatures, the 65 KI-AgI nuclei show excellent activities at lower temperatures, despite the fact that uncomplexed silver iodide cannot be detected by X-ray diffraction.

Nuclei having a molar ratio of 65 KI to one AgI (97.87 wt. % KI, 2.13 wt % AgI) are completely soluble when sufficient water is acquired to yield a composition of 39 wt % water and 61 wt. % of the nuclei material. Precipitation of silver iodide occurs when sufficient additional water is acquired to yield a composition of 84.75 wt. % water and 15.25% nuclei material. These data are based on solubility data obtained at 25C and will be altered at lower temperatures.

5. CONCLUSIONS

Fine particle dispersions of alkali iodide-silver iodide complexes can be generated by pyrotechnic combustion and show excellent activity

as artificial ice nuclei. The activity cannot, in many instances be attributed solely to the silver iodide content of the complexes, but must involve the complexes as entities. Physical and chemical changes in the nuclei, i.e., hydration, decomposition of complexes, and changes in crystal structure are possible prior to the nucleation step.

Comparison of ice nuclei activity spectra obtained on identical pyrotechnic formulations by different techniques suggest that generation of nuclei in supercooled fogs enhances the possibility of contact nucleation, whereas dilution of injection of nuclei smoke samples into supercooled fogs reduces the possibility of contact nucleation; diffusional processes then predominate.

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DePena, R. G., and E. A. Caimi, 1967: Hygroscopicity and Chemical Composition of Silver Iodide Smoke Used in Cloud Seeding Experiments. J. Atmos Sci., 24, 383-386.

Mellor, J. W., 1946: A Comprehensive Treatise on Inorganic and Theoretical Chemistry, Vol. III. new York. Longmans, Green and Co., 432-433.

Steele, R. L., and F. W. Krebs, 1967: Characteristics of AgI Ice Nuclei Originating from Anhydrous NH_3-AgI Complexes. Pt. 1. J. Appl. Meteor., 6, 105-113.

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TABLE 1. Alkali Iodide-Silver iodide Complexes

Literature citations	NWC laboratory evidence
LiI-2AgI	-----
NaI-AgI	NaI-AgI (possible high temp. form)
NaI-AgI-3.5 H_2o	NaI-AgI-3 H_2O
NaI-2AgI	NaI-2AgI (possible high temp. form, hydrate possible)
KI-AgI	KI-AgI (fusion)
KI-AgI-0.5 H_2O	KI-AgI-0.5 H_2O
KI-3AgI	KI-2AgI (possible, fusion)
KI-4AgI	2KI-AgI (fusion)
2KI-AgI	2KI-AgI-H_2O
3KI-AgI-0.5 H_2O	2KI-3AgI (fusion)
3KI-AgI-H_2O	2KI-3AgI (acetone sol.)
	2KI-3AgI (high temp. form)
	3KI-AgI (fusion)
	3KI-2AgI (fusion)
	3KI-2AgI (high temp. form)
RbI-AgI	-----
RbI-AgI-0.5 H_2O	-----
RbI-2AgI	-----
RbI-3AgI	-----
2RbI-AgI	-----
CsI-AgI	CsI-AgI (fusion)
CsI-2AgI	CsI-AgI (solids in contact with

TABLE 1. (contd.)

Literature citations	NWC laboratory evidence
2CsI-AgI	CsI-AgI acetone solution)
	CsI-AgI (high temp form)
	CsI-2AgI (fusion, H_2O ppt)
	CsI-2AgI (high temp. form)
	CsI-3AgI (high temp. form)
	2CsI-AgI (high temp. form)

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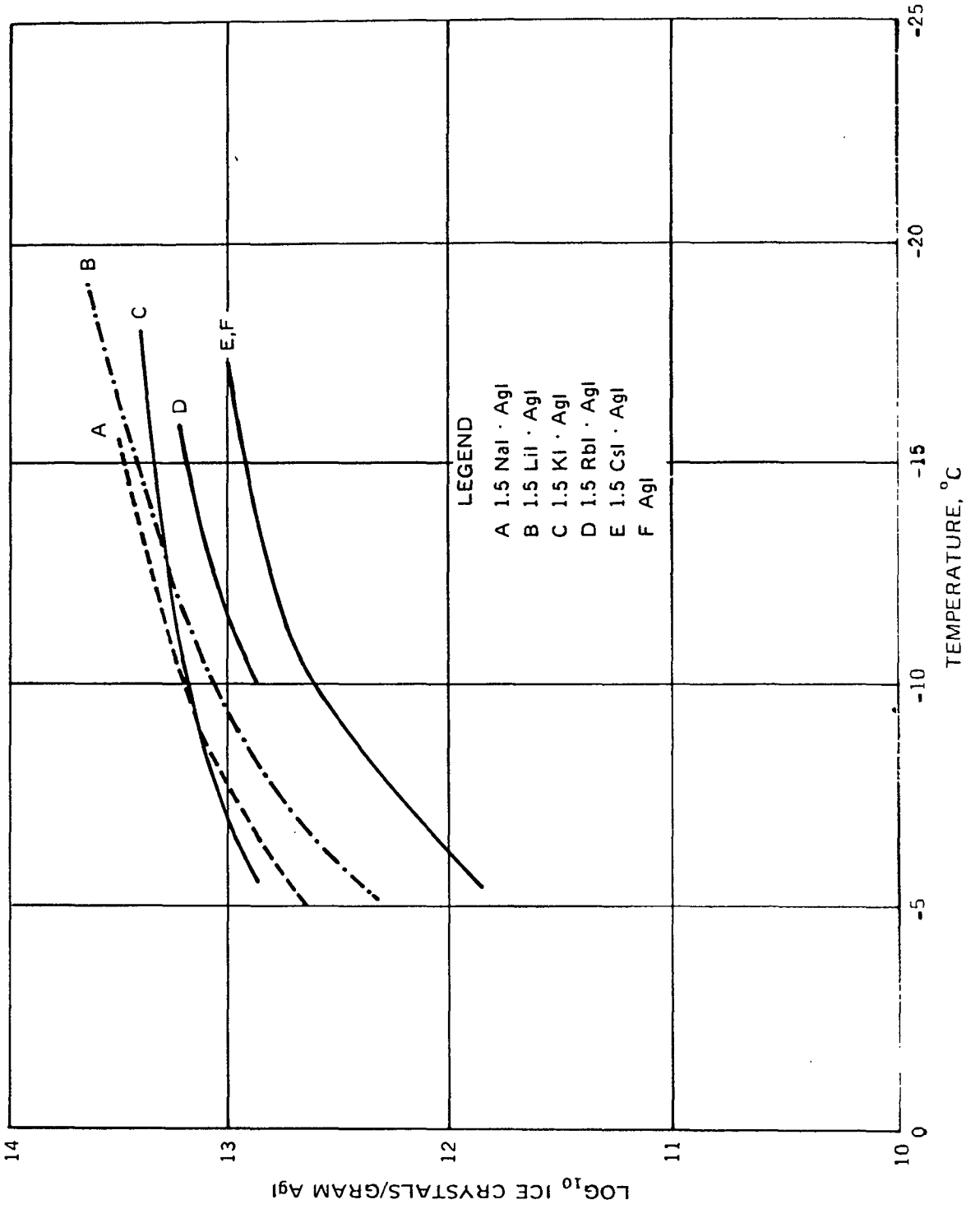
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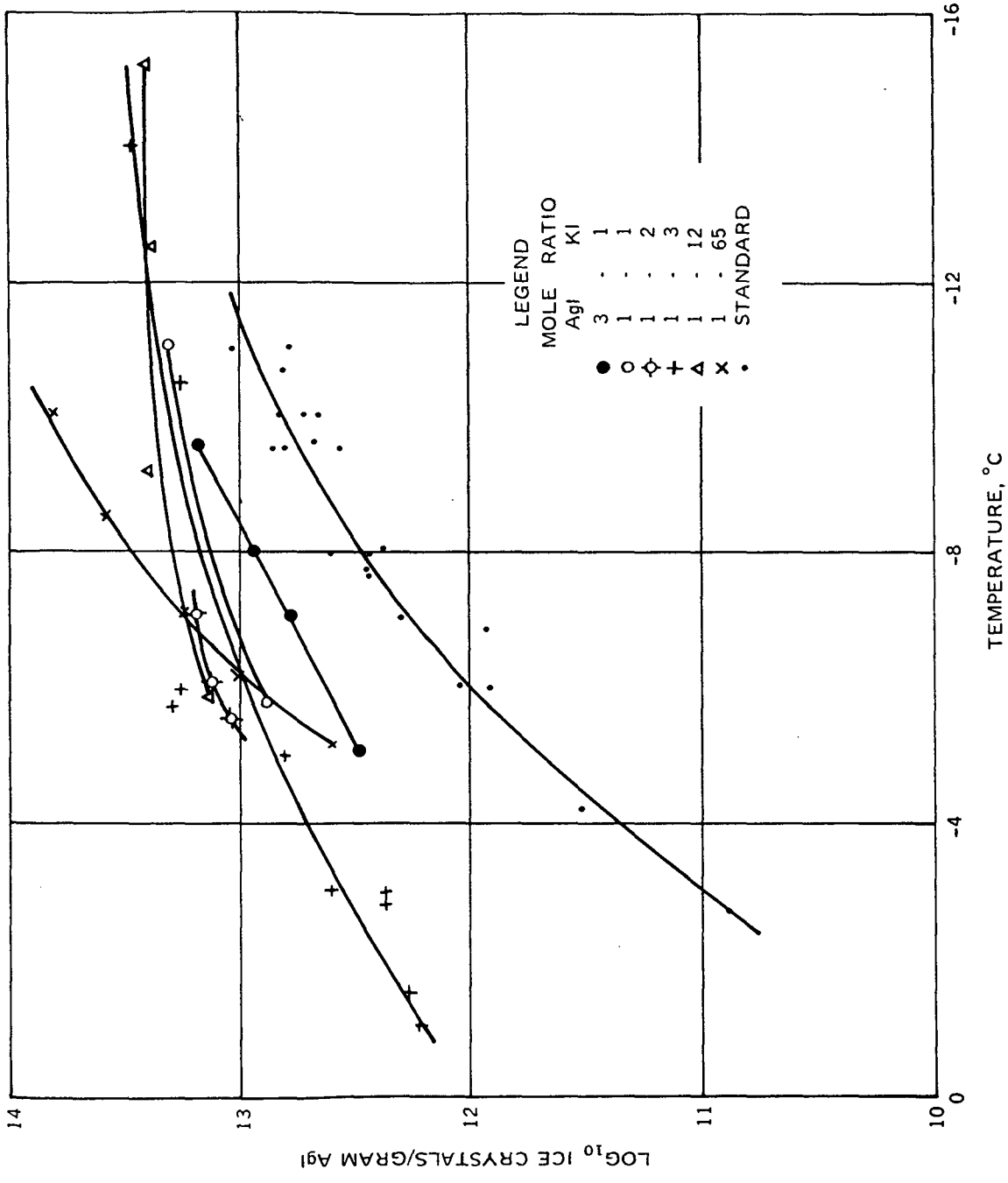
13
12
11
10
0
-5
-10
-15
-20
-25
TEMPERATURE, °C
A
B
C
D
E,F
LEGEND
A 1.5 NaI · AgI
B 1.5 LiI · AgI
C 1.5 KI · AgI
D 1.5 RbI · AgI
E 1.5 CsI · AgI
F AgI


LEGEND
MOLE RATIO
AgI KI
3 - 1
1 - 1
1 - 2
1 - 3
1 - 12
1 - 65
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12
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-12
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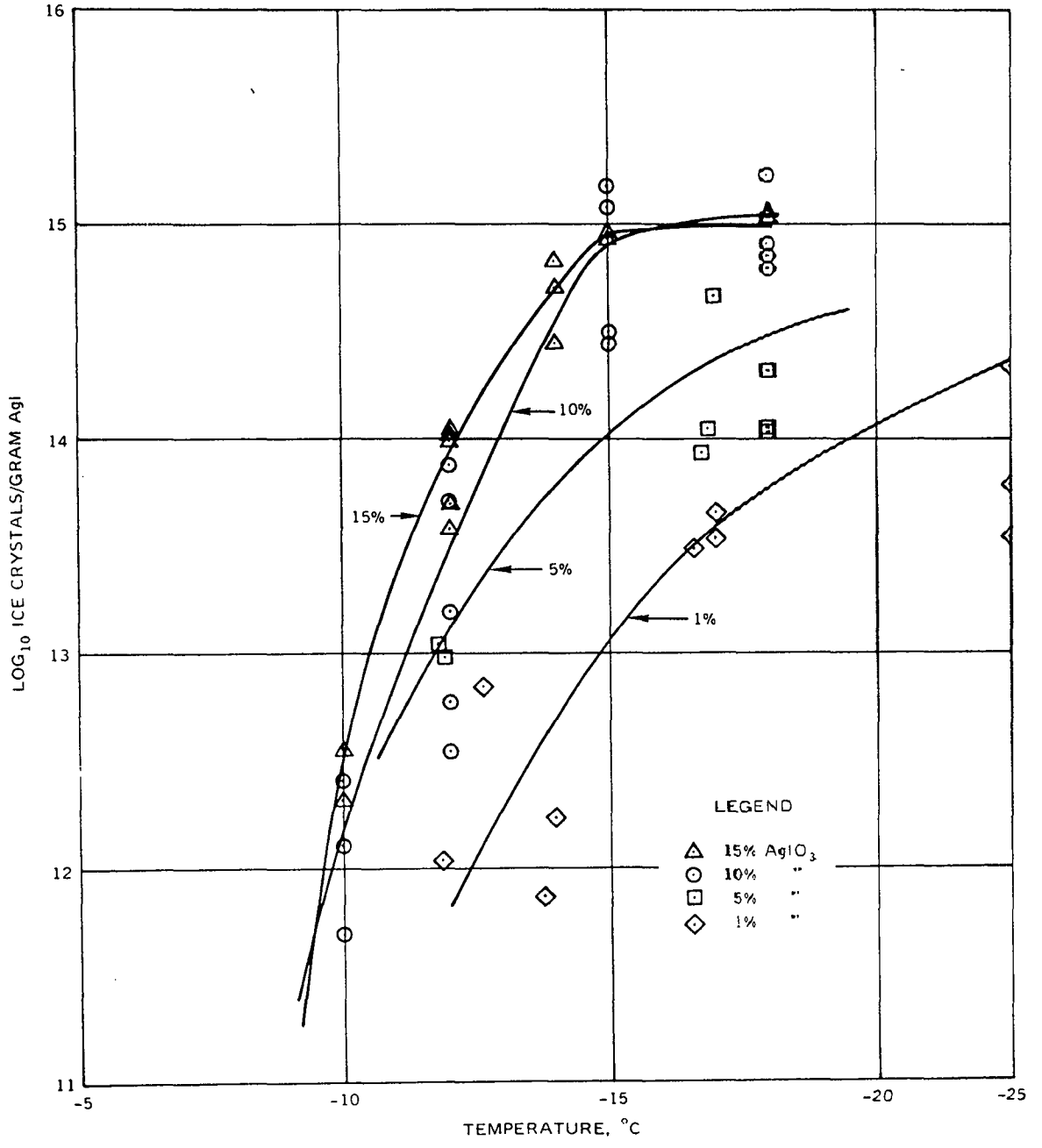
TEMPERATURE, °C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1% "

PYROTECHNIC PRODUCTION OF NUCLEANTS FOR CLOUD MODIFICATION

PART V. Devices for Massive Seeding and Hurricane Modification

Pierre St. Amand, Lohr A. Burkardt, William G. Finnegan, Glenn V. Binns, John B. Burmeister, Ronald F. Vetter, J. A. Donnan and Otho E. Hart

Naval Weapons Center, China Lake, Calif.

ABSTRACT

Cyclops I, a parachute-retarded, nonpropulsive rocket motor delivering 4.5 kg of silver iodide smoke, was used in Project Cyclops, the forerunner of Project Stormfury, in 1961. Cyclops II, a polybutadiene fueled propulsive rocket motor equipped with fins that cause it to describe a helix as it falls, was used in hurricane Beulah in 1963. It delivers 30 kg of silver iodide smoke. Alecto is a polybutadiene fueled rocket motor launched from the M123 photoflash dispenser. It produces 1.7 kg of silver iodide. Imperfect centering of the nozzles imparts an erratic trajectory to encourage mixing with the air. It may be used as a fixed flare for horizontal seeding.

Trajectories, mass flow, and nuclei production rates as a function of altitude are given for Alecto.

I. INTRODUCTION

Pyrotechnic delivery of nucleants offers a good means of delivering sufficient material to modify the energy balance of a major storm system in a time span that is short compared to the life of the clouds comprising the system. Several devices have been developed for seeding large storm systems. The first of these was Cyclops I, a unit developed and used on Hurricane Esther in 1961. Cyclops II and Alecto were developed in 1962.

Cyclops I. The first experiment involving seeding a hurricane with a pyrotechnic device was done with Cyclops I. Fig. 1 shows the overall construction. The grain was composed of P-65, a nitrasol composition also called Argentasol 5052. It delivered 4.5 kg of silver iodide smoke over a vertical distance of 20,000 ft. Upon release from the aircraft, in this case a Navy A-3 Skywarrior, the flare was stabilized by stubby tail fins until it had fallen free of the aircraft. After 2 sec a pair of pyrotechnic shroud cutters severed the nylon cord that held the tail assembly together. A spring then forced the tail fin assembly away, and a ribbon parachute was released. The opening shock

of the parachute actuated the fuze, igniting a match and delay train. Following another few seconds' delay, while the aircraft was pulling away from the parachute-retarded flare, the delay train ignited a transfer charge that set off an igniter. The igniter passed through the length of the grain in an inhibited hole and set fire to the front face of the grain by means of a circular piece of aluminum window screen (not shown) painted with a first fire mix of aluminum, magnesium, viton, and polyvinylmethyltetrazole (PMVT). When the grain was ignited, the exhaust gases escaped through an internal nozzle into a graphite-lined space and out a series of nonpropulsive ports. The duration of burn was carefully adjusted to give the vertical fall distance required when dropped from 40,000 ft.

Because some preliminary trouble was experienced with the rather involved ignition train, a telemetering device was incorporated onto the ends of the flares to indicate when the temperature rose sufficiently to ensure ignition. Because of the parachute and the heavy metal case, the vertical velocity was almost constant while the grain was being consumed. The devices traveled forward a little less than a mile even though they were dropped at speeds of 220 knots. Static tests indicated that reliable ignition could be obtained at altitudes in excess of 50,000 ft. after the devices had been cooled to -65C for periods in excess of 3 hrs.

The project was begun in late June 1961, and the units had been designed, built, tested, and shipped to Puerto Rico by 12 September. On 16 September the first eight units were dropped at 5-sec intervals from an A-3 aircraft from Heavy Attack Squadron 11 flown by Lt. John Shattuck and Lt. Frank O. Baty. Another sortie was made the next day, and the hurricane was again seeded with eight units.

Cyclops II. Cyclops I was complicated and expensive because it had been put together in such a short time. More of these units were desired, but because of the high cost we decided to develop a new type of unit. It was still thought that the cloud wall in the eye of the hurricane was the best place to seed, and the amounts required were very large. We therefore, developed Cyclops II, a considerably simplified version of Cyclops I, and Alecto, a much simpler, smaller unit.

During the winter of 1961 further development of nitrasol compounds was suspended for safety reasons, and it became necessary to use other propellants. The polybutadiene fuels were developed for the new units, and after several trials CY 21 was adopted.

Cyclops II was a fin-retarded rocket motor (Fig. 2) that relased about 30 kg of silver iodide smoke. The folding fins were secured to the body of the flare by a nylon cord. Short fins stabilized the device until it had fallen free of the aircraft. After a 5-sec delay the nylon cord was severed by a pyrotechnic cutter, and the fins were dragged open by small air scoops. The opening of the fins actuated

an impulse magneto, and this in turn lit an igniter which set fire to the main grain. The nozzle configuration was designed to produce a minimum of thrust and a maximum of turbulence. The smoke exhausted into a ported section designed so as to maximize mixing with the air. One of the three fins was smaller than the others, and this imparted a circular motion to the falling flare so that it described a helix as it fell. The diameter of the helix was about 200 yds. (Fig. 3).

Cyclops II operated at a pressure of 100 to 200 psi and burned for about 45 sec.

No data are available on the nucleation effectiveness of this device, and the data from Alecto are probably not applicable because of Alecto's much higher internal pressure. The results will not differ by much at the warmer temperatures but will probably be less at the colder temperatures.

Cyclops II was used in Hurricane Beulah in 1963. Production of these units has been suspended because the charge is too large. The dispersion of single large charges is not as effective as the dispersion of smaller doses spread throughout the cloud system.

Alecto. Captain William Eason, USN, called to our attention the photoflash systems used by the U.S. Armed Forces and suggested that we turn our efforts to the development of a series of smaller units that could be dispensed in greater quantity. This suggestion proved fruitful, and we proceeded with the design of two types of units. One was a 1.5--inch--diameter rocket motor that could be fired by the M112 photoflash dispenser. The unit was produced in limited quantity but was abandoned because the metalwork and construction costs were excessive for the amounts of silver iodide produced by one unit. A larger unit dispensed by the M123 photoflash dispenser was finally selected for development. The high-altitude system requirements still made necessary the use of enclosed rocket motors so that the material would ignite and burn under the conditions demanded by the experiment. Since then we have succeeded in making pressed pyrotechnics that burn beautifully at high altitude, so that Alecto is now technoligically passé.

The unit produced in quantity and used in Project Stormfury is shown in Fig. 4. It consists of a rocket motor enclosed in a large aluminum cartridge. This motor is fired by an electrical impulse to the primer. The primer ignites a boron-potassium nitrate charge that ignites a magnesium-Teflon igniter. The igniter design serves as a time delay and sets fire to the main grain after a delay of about a second. The production units, when filled with CY 21, burn for about 45 sec. This gives a smoke production of 1.7 kg of silver iodide over a vertical fall of about 15,000 ft. The burn time can be controlled by changing the nozzle diameter.

The rocket motor case is made of drawn steel and is lined with a fiber glass heat barrier. The graphite nozzle is imbedded in a steel

end plate. The nozzle is constructed so as to produce a maximum of turbulence to ensure rapid mixing of the products with the surrounding air. The units produce about 15 lb of thrust, and the nozzles are sufficiently imperfectly centered to produce rotation, spinning, and tumbling of the units to further encourage mixing of the smoke with the surrounding air. Because the unit is end-burning, the unstable flight ceases as the center of gravity of the unit moves forward.

The internal pressure of the Alectos using CY21 varies from 200 to 500 psi. Fig. 5 shows the internal pressure as a function of time for a unit that burned for 39 sec. Fig. 6 shows the mass flow in grams per second from the unit. Fig. 7 shows the position vertically and horizontally as a function of time of an Alecto that burned for 39 sec., dropped from a height of 35,000 ft from an aircraft flying at 220 knots, indicated airspeed. Fig. 8 shows the horizontal and vertical distances and velocities. Fig. 9 shows the mass flow as a function of height below the drop point.

Using the data reported by Colorado State University in another of these articles, we show, Fig. 10, the number of nuclei effective at a given altitude as a function of drop height for an atmosphere having a standard lapse rate. We realize that different lapse rates are possible and include this figure only to illustrate the type of calculation possible. Further, it should be remembered that the number of nuclei available in a real cloud is probably much greater than these curves would indicate.

A number of Alecto CY35s were made. The behavior of these units is slightly different in that the burn time is longer and the number of nuclei effective at warmer temperatures is greater. The action of the nuclei is basically identical. Similar calculations could be made for these, although the irregularities of burn time and of internal pressure would make it difficult to assess the value of the calculation.

a. Dispensing systems. Fig. 11 shows a typical dispensing unit for Alecto. These modules may be mounted in or on aircraft and will dispense Alecto individually or at preselected intervals. Fig. 12 shows the bomb bay of an A-3 aircraft equipped to dispense a plurality of Cyclops II and 320 Alecto. The mode of release is controlled by the bombardier. Any or all of the units may be salvoed in the event of emergency.

b. Tethered Alecto. A variation of the Alecto that has proved useful for seeding Great Plains thunderstorms or in any application where release of large amounts of material along a horizontal line is desired is shown in Fig. 13. An additional hole has been borned in the nozzle plate and threaded to receive a modified pipe plug which holds an ignition squib in place. These units may be clamped onto an aircraft and burned while in flight. The end cap closures have been made weak deliberately so that in the event of a plugged nozzle or abnormal burning, the nozzle plate will blow off when the internal pressure

reaches about 1,000 psi. The case is much stronger and will not rupture first. Another part of this series outlines the use of several of these units on a large thunderstorm.

Uses. These devices cannot be used over land because of the hazard of falling motor cases. They are adaptable to use on large storm systems such as hurricanes and typhoons. They will probably be replaced by pressed pyrotechnics when we learn how much nucleant is really needed to work on these large storms. At present, however, they are the only really effective way of doing massive seeding and are far superior to any conventional technique.

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DEVICES FOR MASSIVE SEEDING
AND
HURRICANE MODIFICATION

FIGURE LEGENDS

FIG. 1. Cyclops I (a) assembled and (b) disassembled.

FIG. 2. Cyclops II (a) assembled and (b) component sketch.

FIG. 3. Smoke trails from two Cyclops IIs.

FIG. 4. Alecto (a) metal case and cutaway and (b) component sketch.

FIG. 5. Internal pressure (Alecto, CY 21) as a function of time.

FIG. 6. Mass flow (Alecto, CY 21) as a function of time.

FIG. 7. Alecto (CY 21) trajectory. Drop was made from 35,000 ft. at 220 knots.

FIG. 8. Alecto horizontal and vertical (a) distances and (b) velocities

FIG. 9. Mass flow (Alecto, CY 21) as a function of altitude below drop point.

FIG. 10. Number of nuclei effective at a given altitude as a function of drop height for an atmosphere having a standard lapse rate.

FIG. 11. Alecto dispenser.

FIG. 12. Bomb bay of A-3 aircraft set up to dispense Cyclops II and Alecto.

FIG. 13. Alecto modified as a fuse to be burned on an aircraft for line seeding. The igntion squib is in the pipe plug; the first-fire igniter is positioned directly opposite the squib.

FIGURE 1 (a)

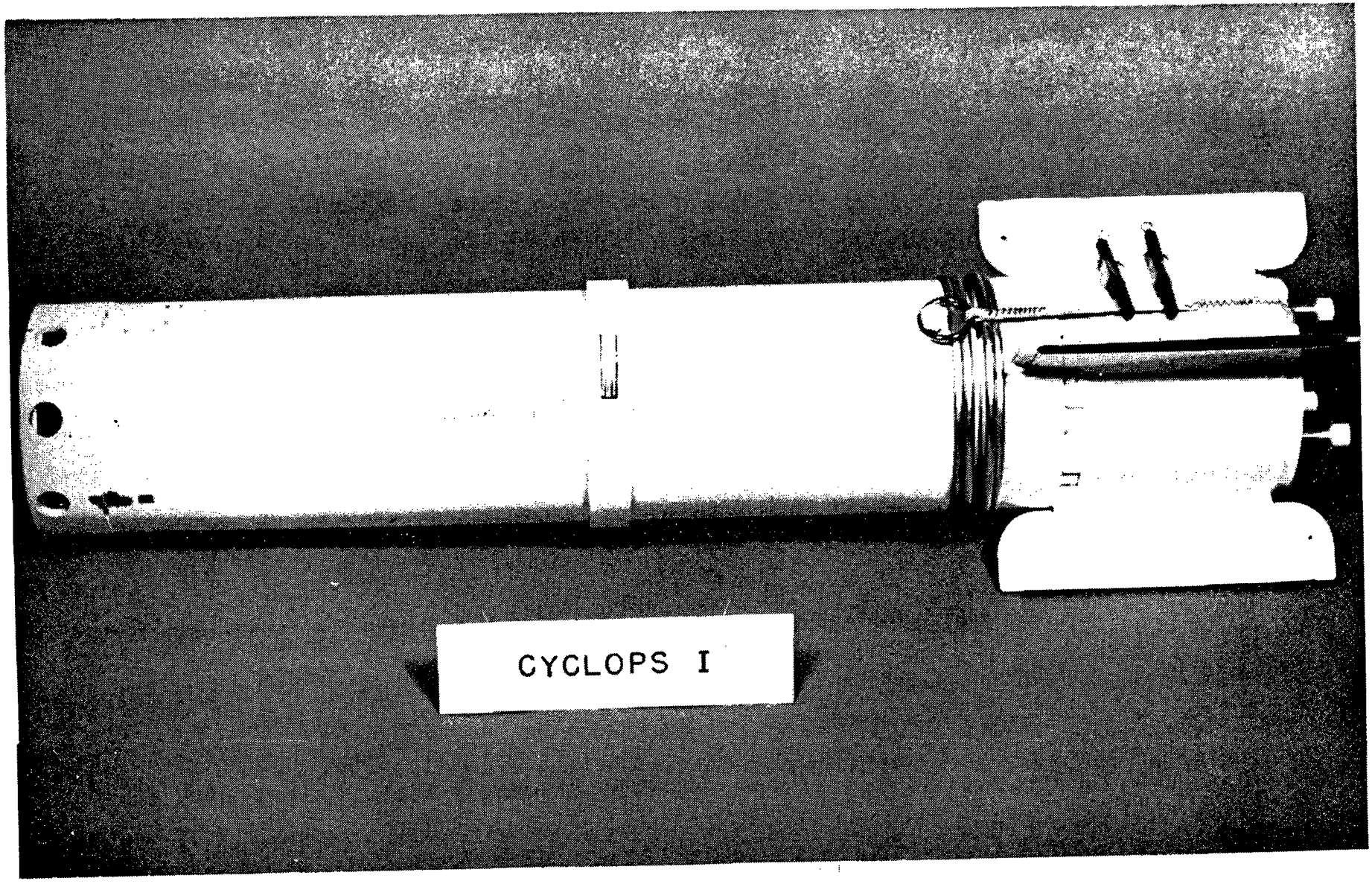


FIGURE 1 (b)

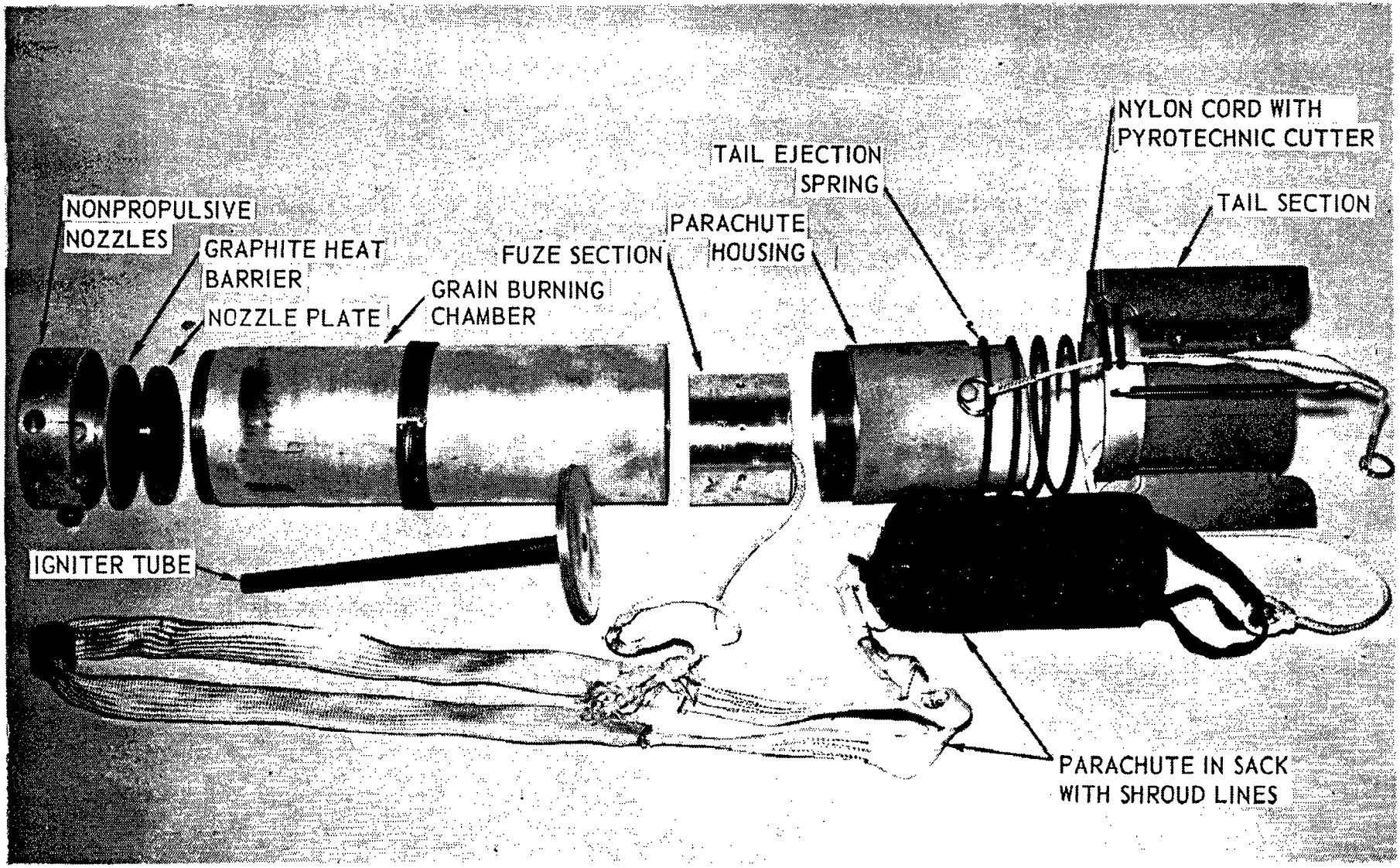

NONPROPULSIVE NOZZLES
GRAPHITE HEAT BARRIER
NOZZLE PLATE
GRAIN BURNING CHAMBER
FUZE SECTION
TAIL EJECTION SPRING
PARACHUTE HOUSING
NYLON CORD WITH PYROTECHNIC CUTTER
TAIL SECTION
IGNITER TUBE
PARACHUTE IN SACK WITH SHROUD LINES

FIGURE 2 (a)

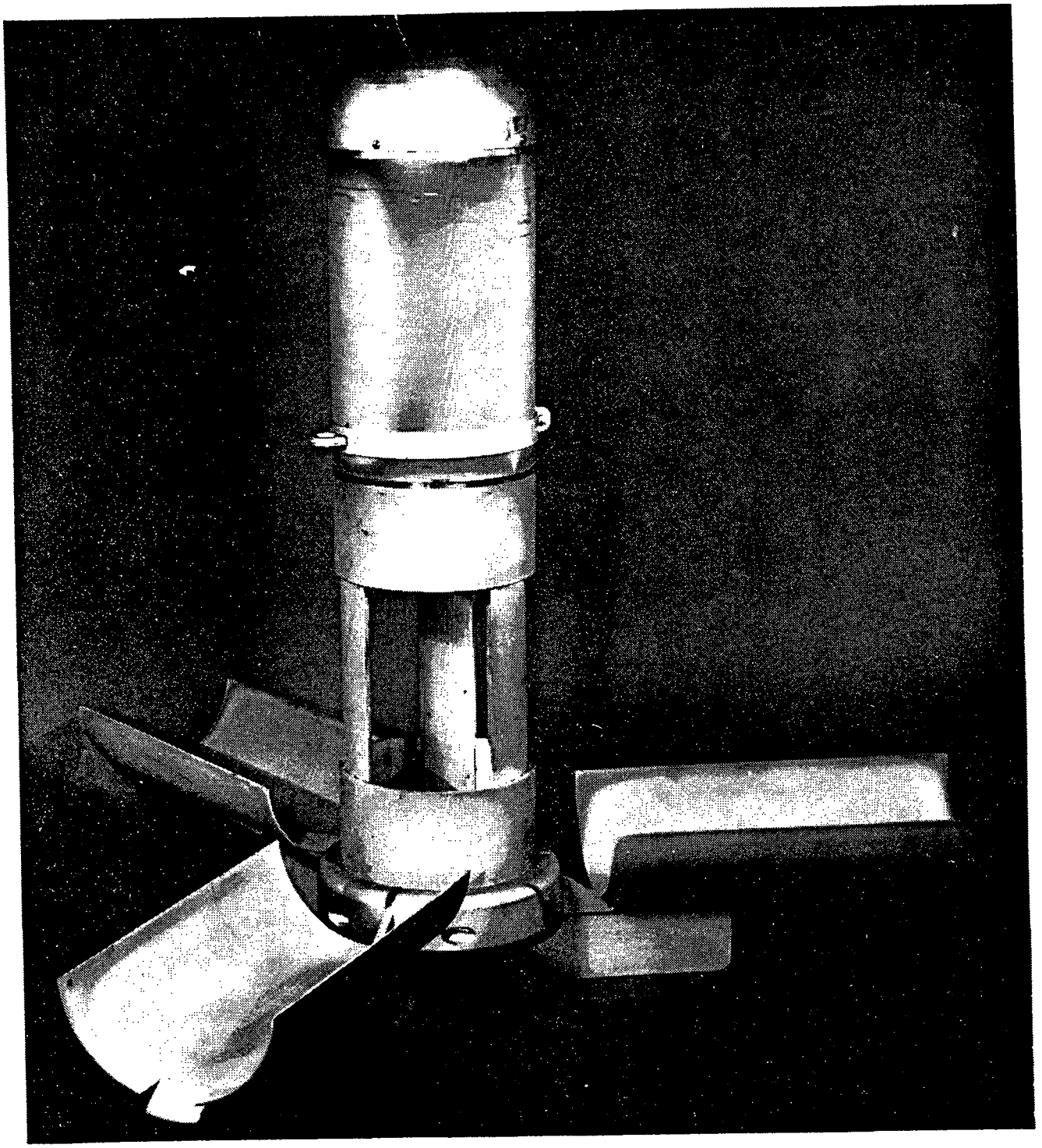


FIGURE 2 (b)

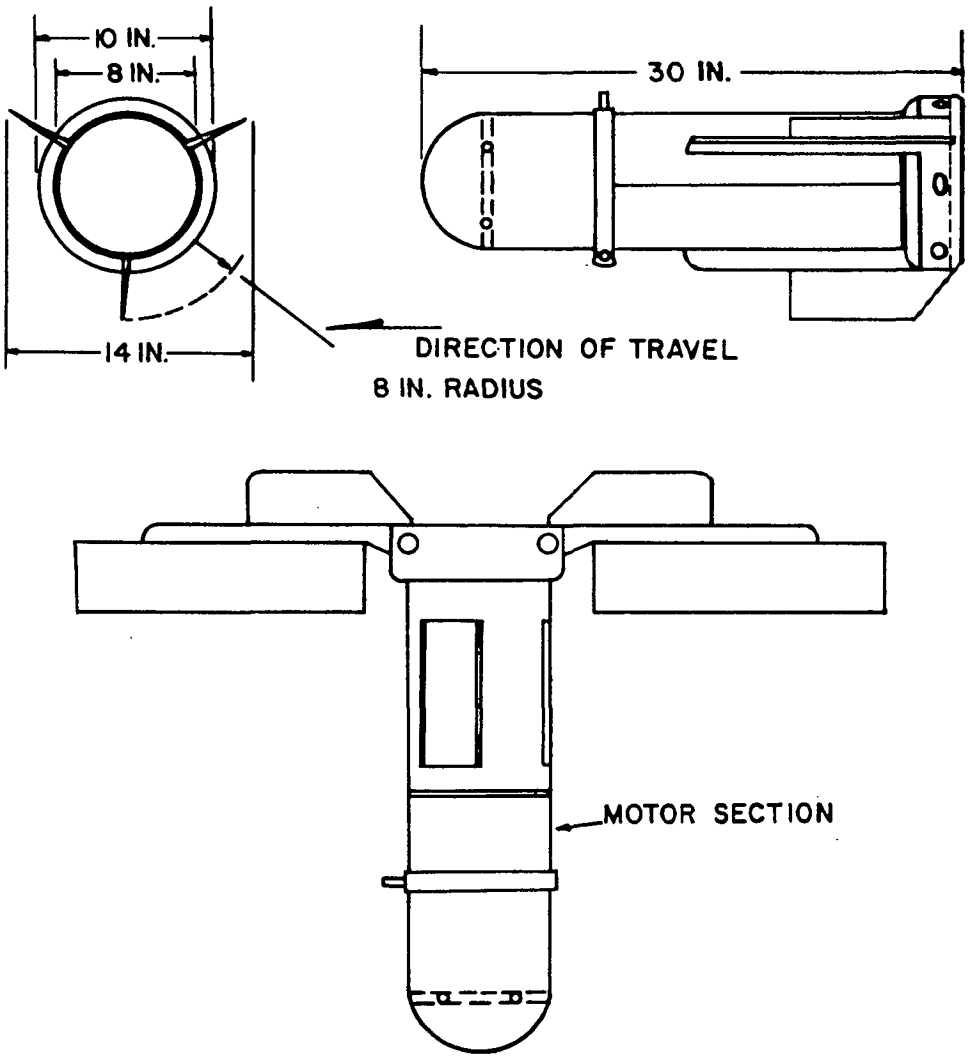

10 IN.
8 IN.
14 IN.
30 IN.
DIRECTION OF TRAVEL
8 IN. RADIUS
MOTOR SECTION

FIGURE 3

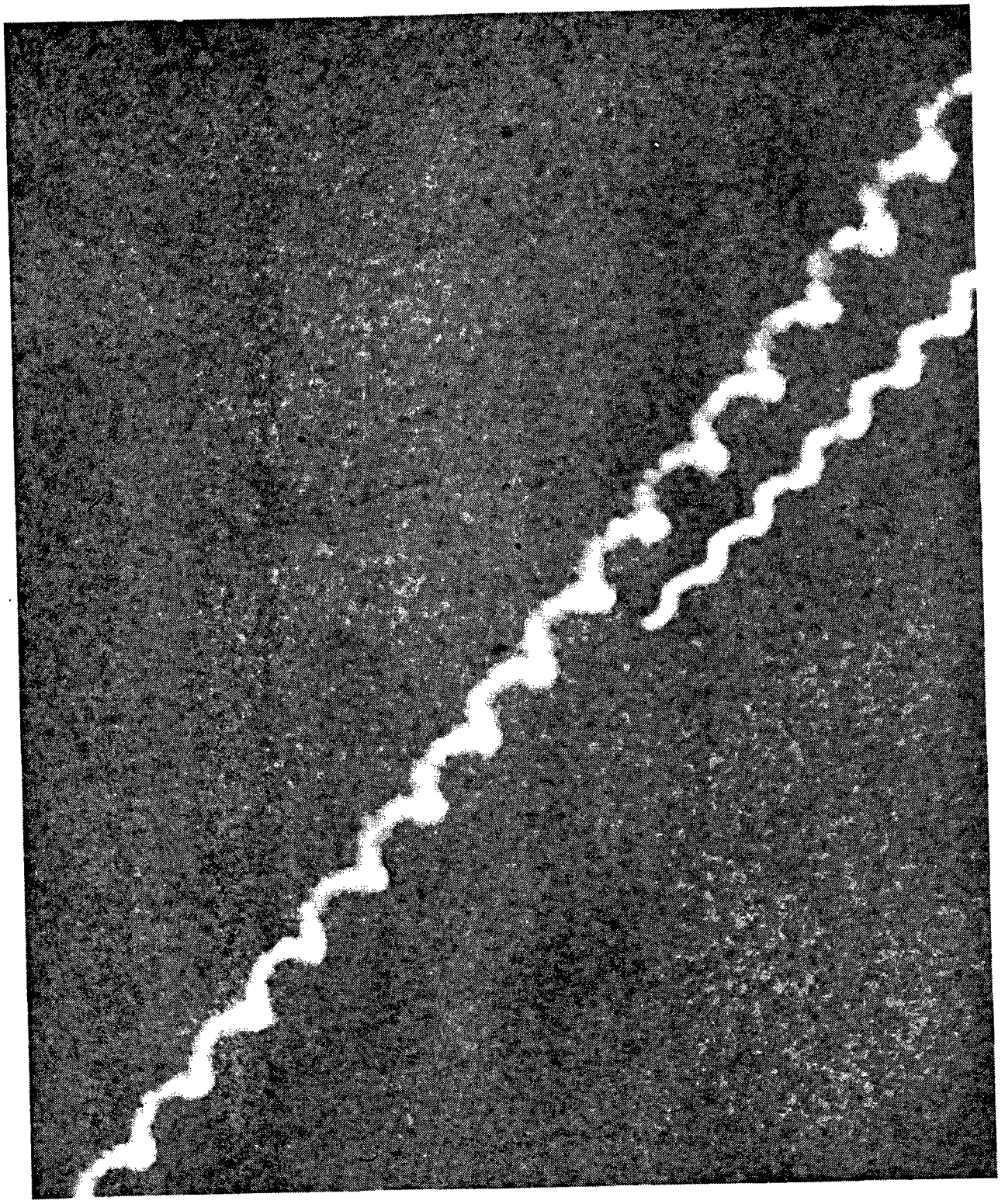
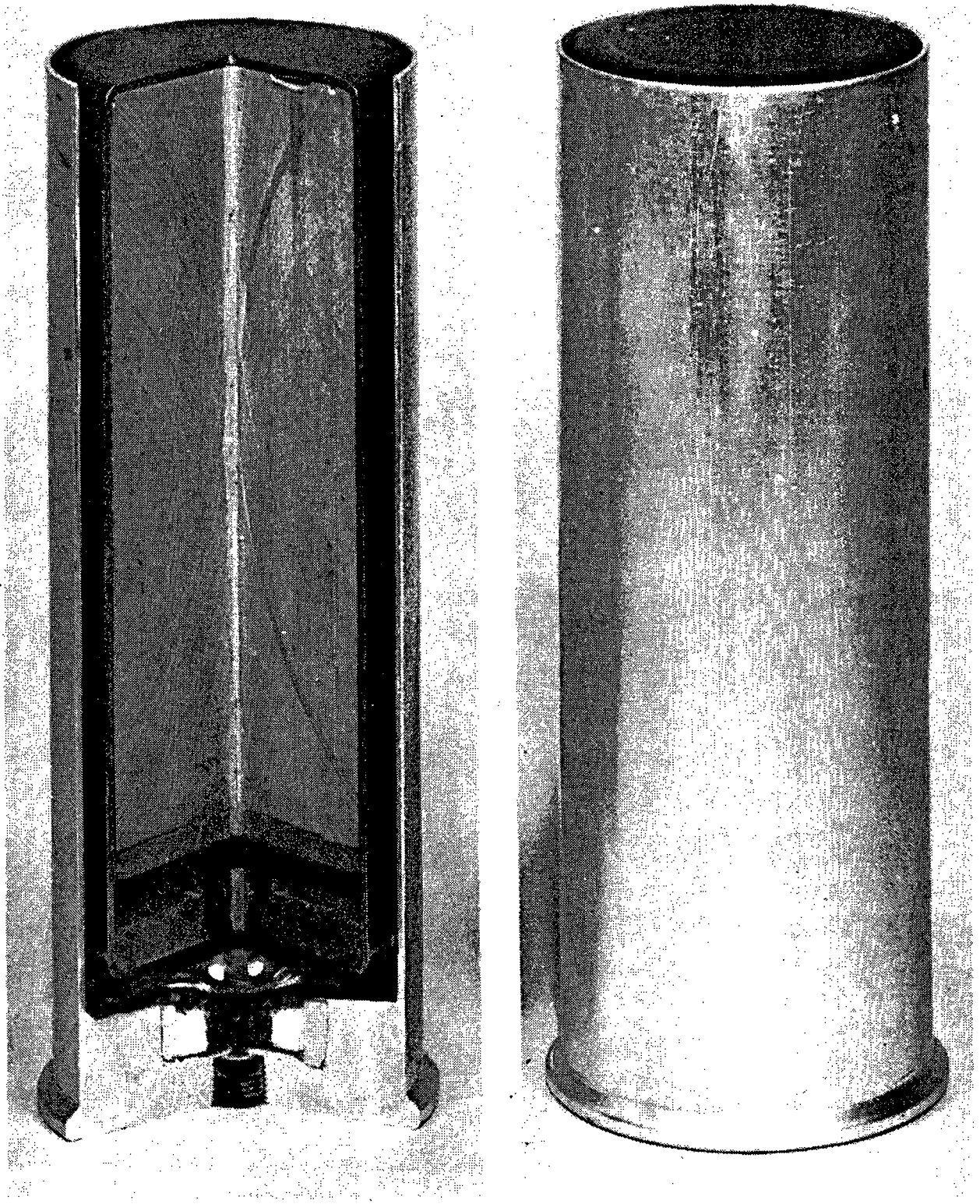


FIGURE 4 (a)



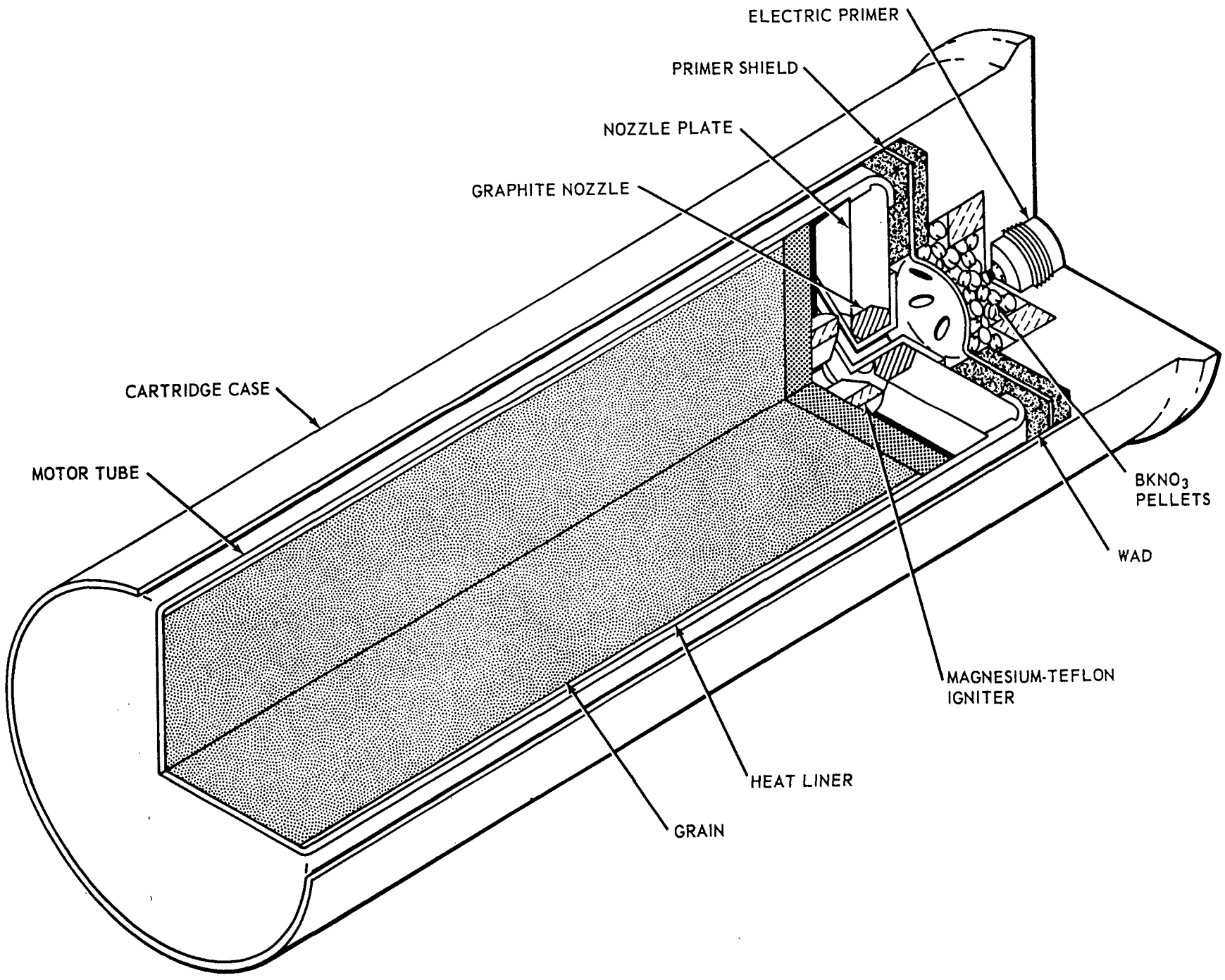

ELECTRIC PRIMER
PRIMER SHIELD
NOZZLE PLATE
GRAPHITE NOZZLE
CARTRIDGE CASE
MOTOR TUBE
$BKNO_3$ PELLETS
WAD
MAGNESIUM-TEFLON IGNITER
HEAT LINER
GRAIN

FIGURE 5

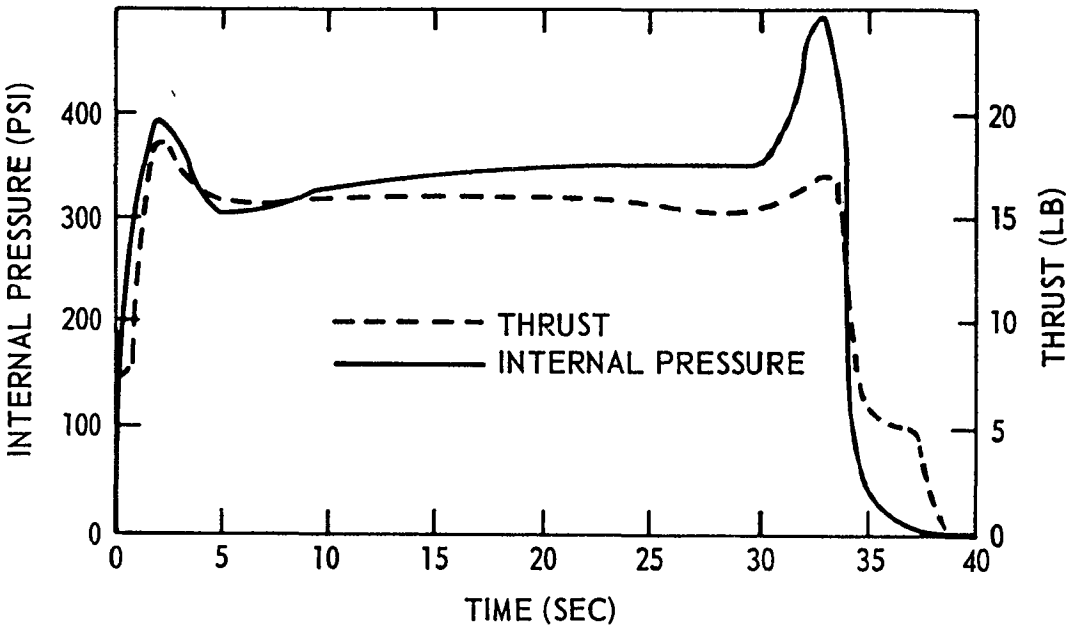


FIGURE 6

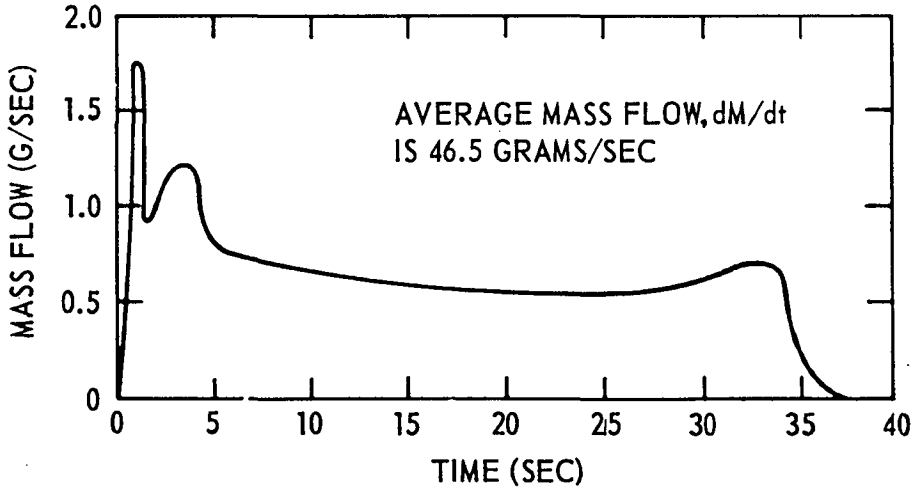


FIGURE 7

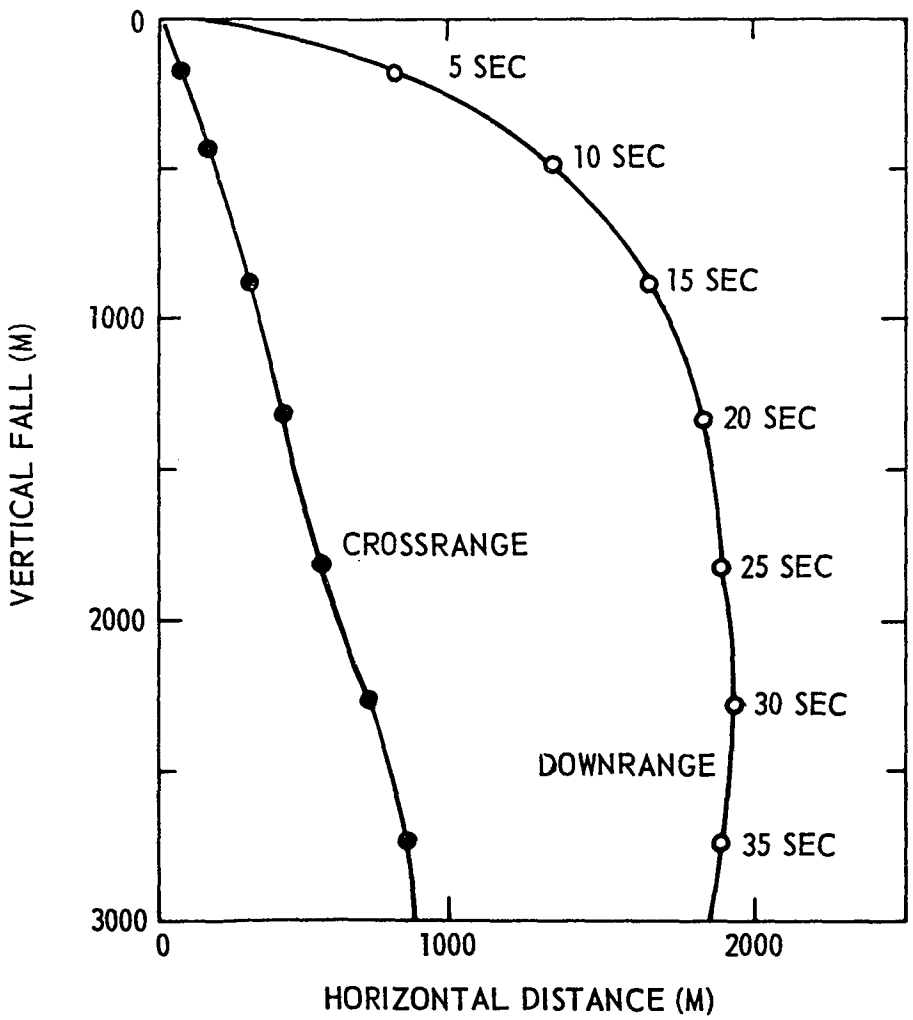

0
1000
2000
3000
VERTICAL FALL (M)
5 SEC
10 SEC
15 SEC
20 SEC
25 SEC
30 SEC
35 SEC
CROSSRANGE
DOWNRANGE
0
1000
2000
HORIZONTAL DISTANCE (M)

FIGURE 8 (a)

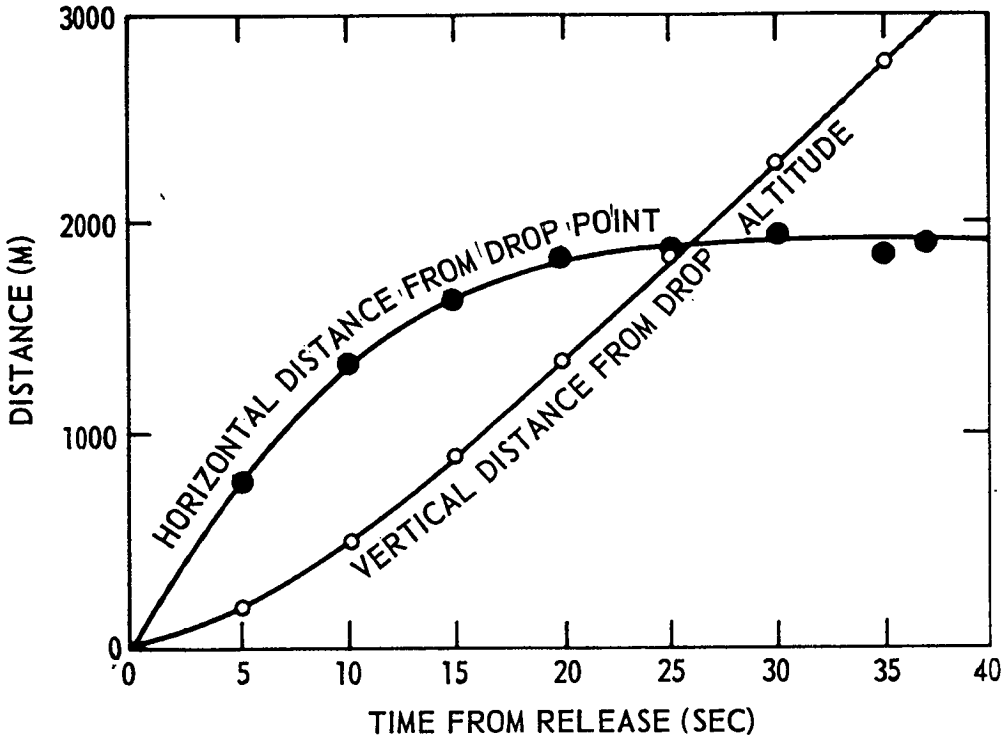


FIGURE 8 (b)

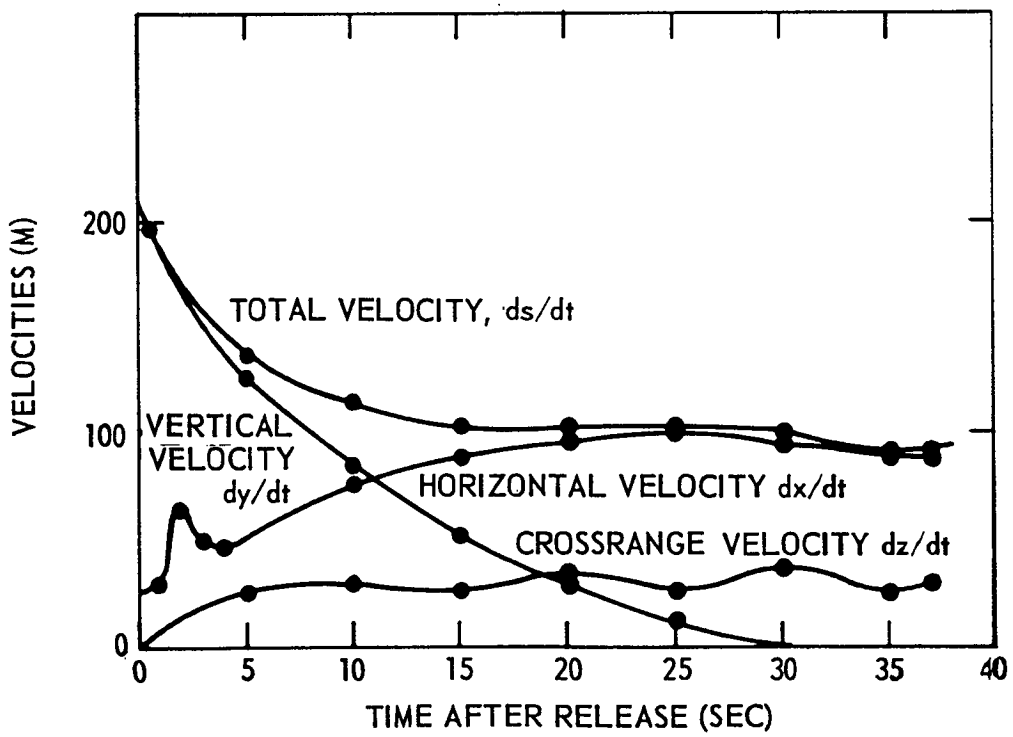


FIGURE 9

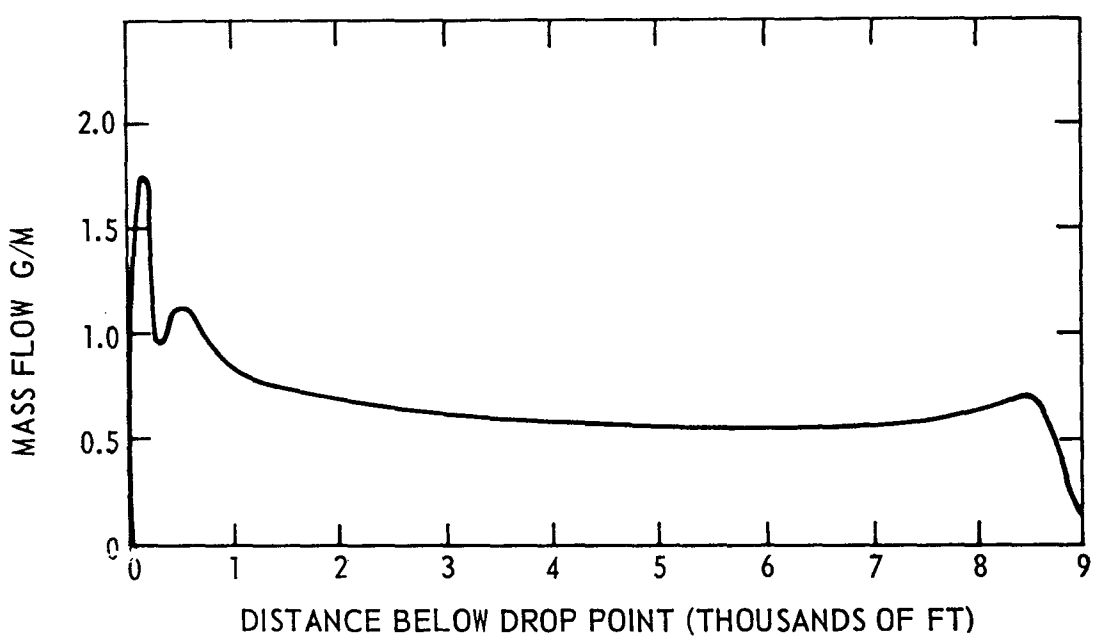

MASS FLOW G/M
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
DISTANCE BELOW DROP POINT (THOUSANDS OF FT)

FIGURE 10

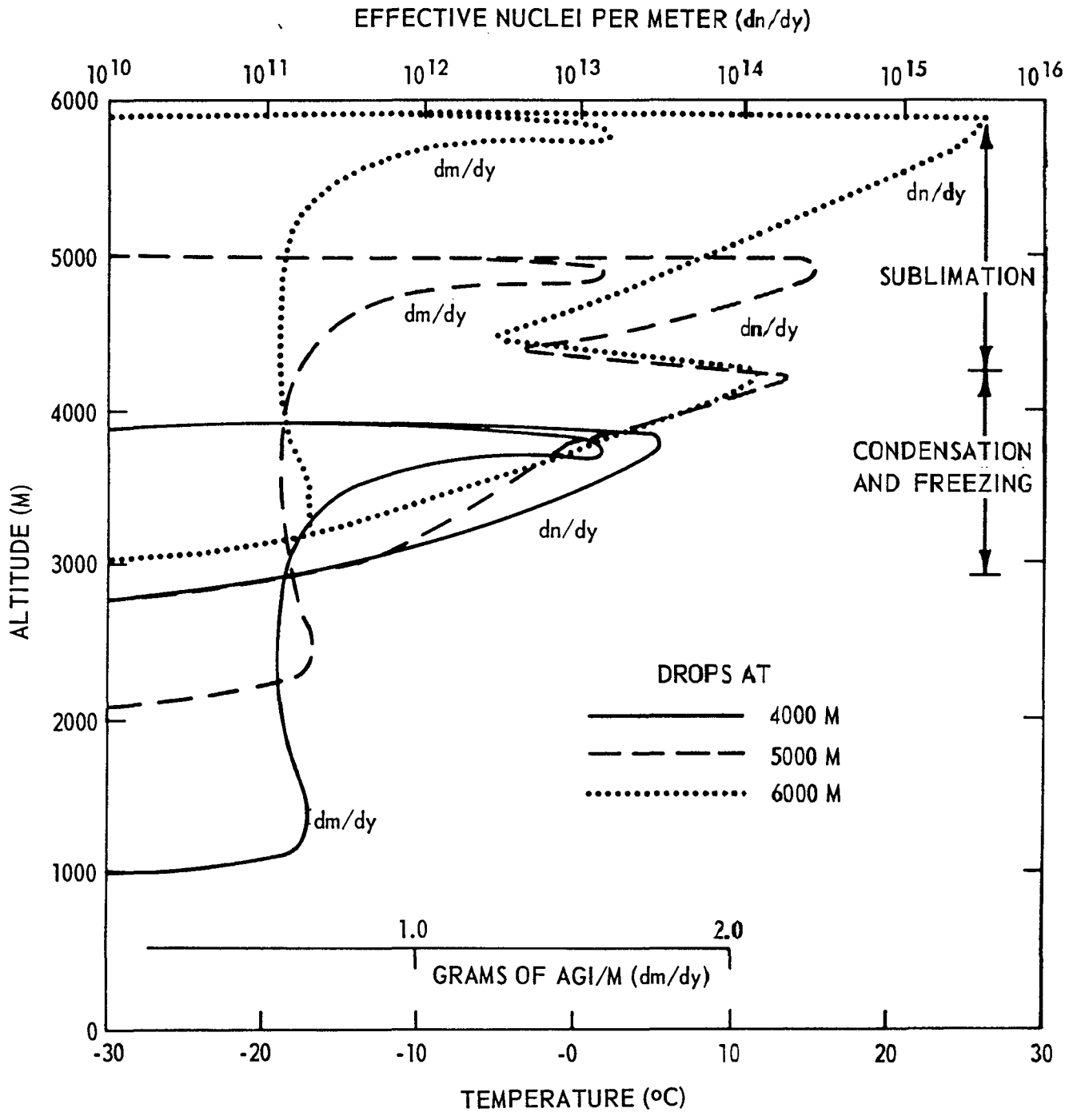

EFFECTIVE NUCLEI PER METER (dn/dy)
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
6000
5000
4000
3000
2000
1000
0
ALTITUDE (M)
dm/dy
dn/dy
dm/dy
dn/dy
dn/dy
dm/dy
SUBLIMATION
CONDENSATION AND FREEZING
DROPS AT
4000 M
5000 M
6000 M
1.0
2.0
GRAMS OF AGI/M (dm/dy)
-30
-20
-10
-0
10
20
30
TEMPERATURE (°C)

FIGURE 11

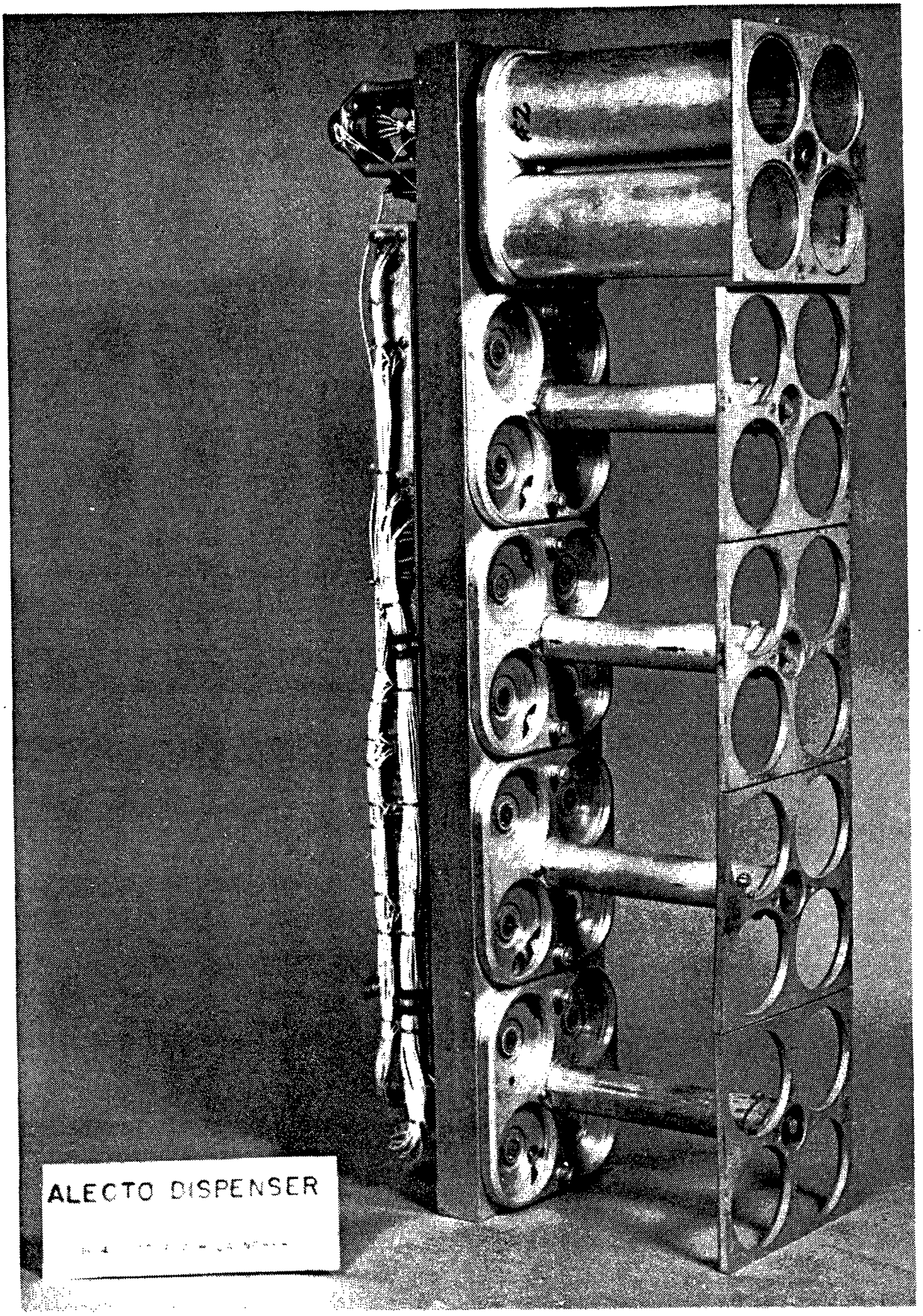
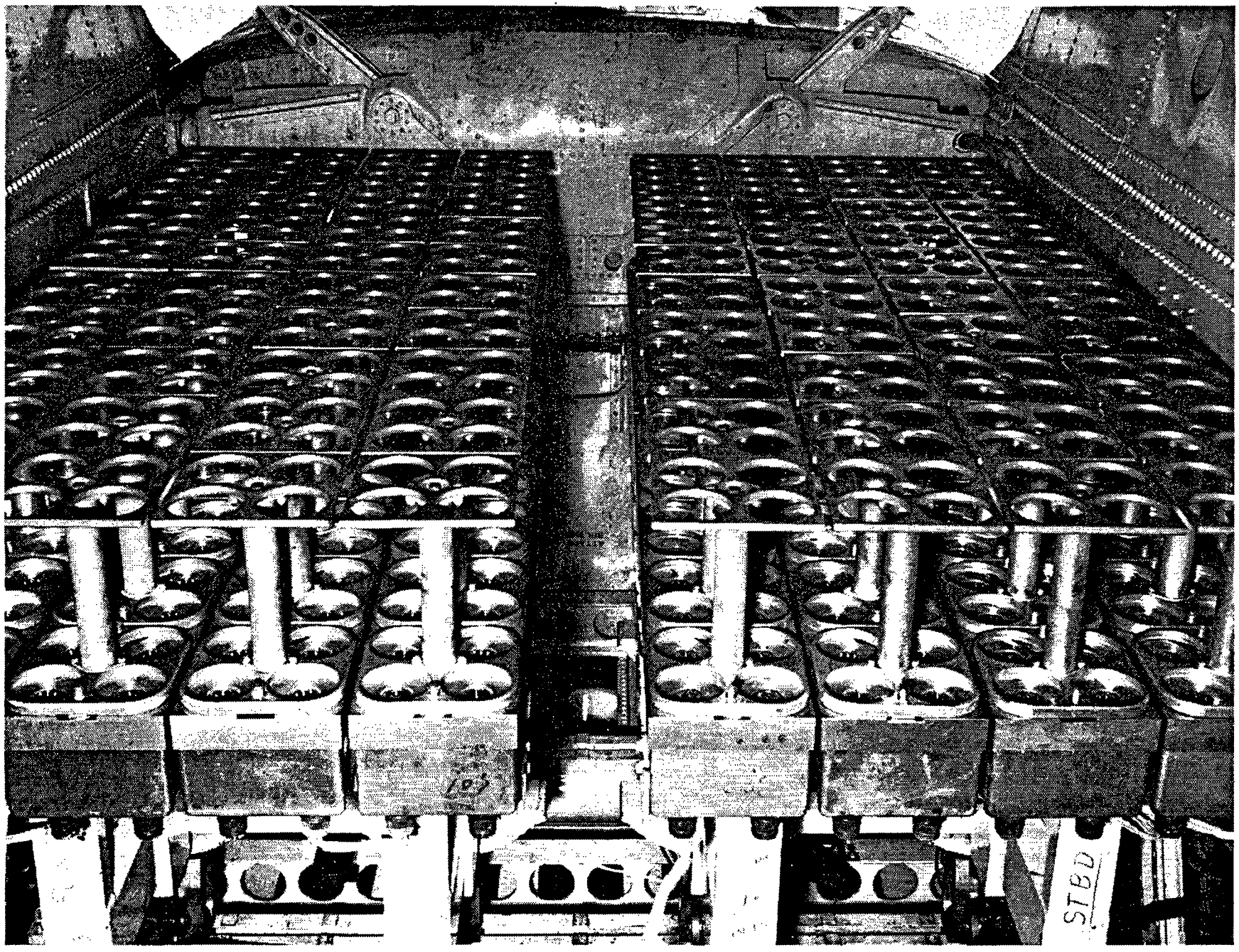


FIGURE 12



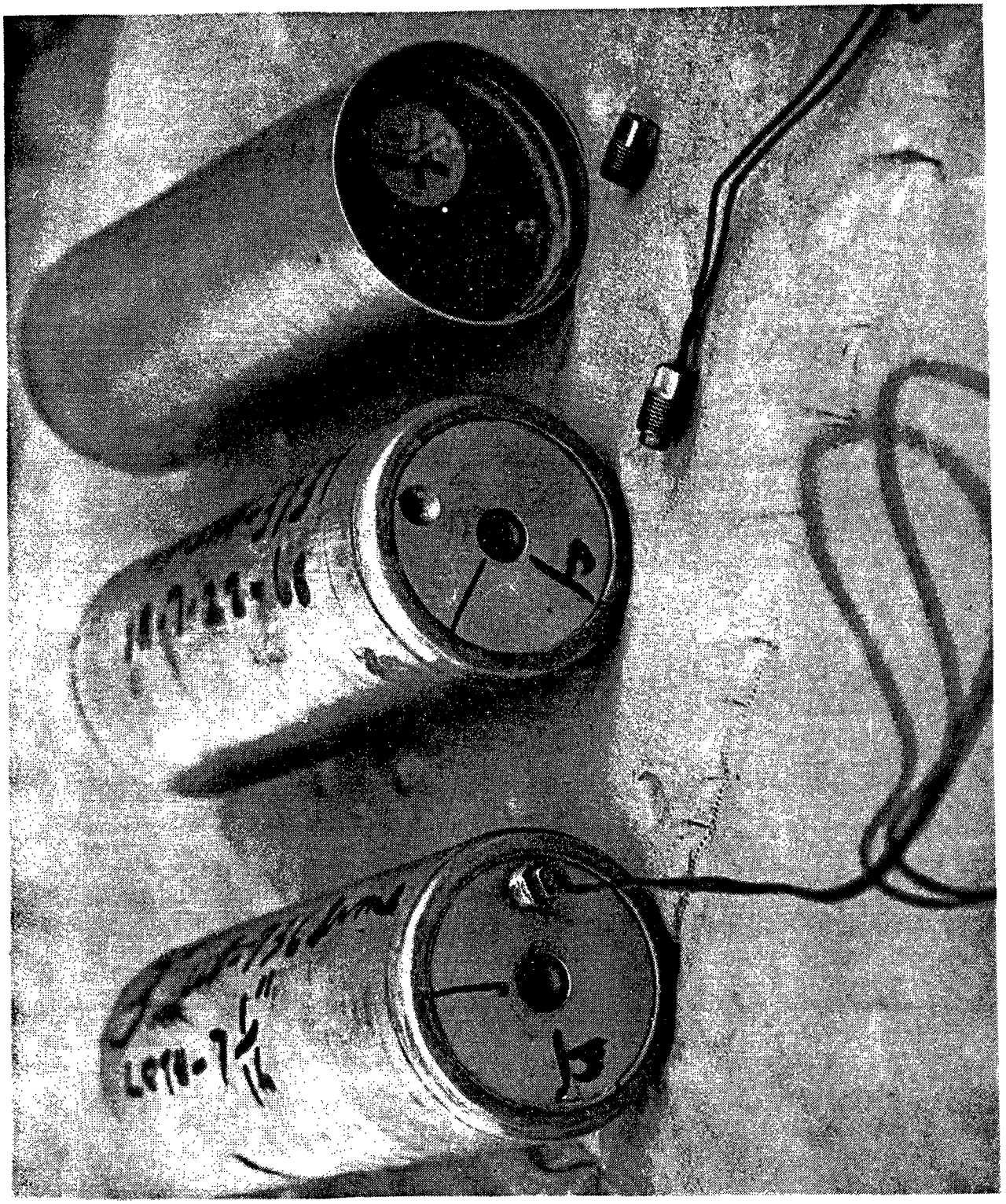


FIGURE 13

PYROTECHNIC PRODUCTION OF NUCLEANTS FOR CLOUD MODIFICATION

Part VI. Case Study of Apparent Stimulation of Convection by Seeding a Thunderstorm with "Alecto" Pyrotechnic Devices

Richard A. Schleusener, Pierre St.-Amand
Wayne Sand and John A. Donnan

Naval Weapons Center, China Lake, Calif.

ABSTRACT

During the summer of 1963, a number of thunderstorms were seeded with silver iodide-alkali iodide nuclei as a part of a hail suppression experiment in northeastern Colorado. One of the storms was treated with relatively pure silver iodide produced by five Alecto units burned in a strong updraft at the northwestern base of the storm. Rainfall increased rapidly. As much as 3 in. fell nearby with amounts as great as 1 in. falling for several tens of miles along the storm track. Rainfall of this intensity occurs less often than once in 12 years. The radar echo from the storm grew rapidly northward and eastward of the seeded area. The northward component of the velocity of the edge of the radar echo averaged 104 knots over a 5-min period. This rate of advance of radar echoes is observed less often than once in 35 years. While it cannot be proved in this way that seeding altered the storm, it is extremely unlikely that the increased growth and increased rainfall were caused by natural processes alone, and it is very likely that artificial stimulation of the convective activity by the silver iodide was responsible for these phenomena. No hail was observed.

1. INTRODUCTION

The primary purpose of the cloud seeding experiments conducted at Colorado State University during the summer of 1963 was to develop procedures for coordinating the activities of seeding aircraft and ground observation systems, and to design randomized experiments that were begun in 1964 and continued in 1965.

As part of these procedures, individual thunderstorms were selected for seeding on a nonrandom basis. The thunderstorm under consideration in this paper was not selected at random, but was chosen as suitable for possible modification.

The selection was based on a number of factors that have since been shown to be significant. The radar tops were above 30,000 ft msl prior to seeding, and the radar echo was firm on all sides, the northern edge in particular. Updrafts, as measured with rate of climb instruments

below cloud base, were in excess of 7 m/sec at numerous points under the cloud base, including the area in which the silver iodide was released. Updrafts in excess of 7 m/sec have subsequently been shown by Auer and Sand (1966) to be a factor associated with potentially severe thunderstorms.

It was considered possible that complete "overseeding" with large numbers of silver iodide crystals might be a mechanism by which hail damage could be reduced. This hypothesis was the basis for the seeding experiment on a developing thunderstorm in northeastern Colorado on 26 July 1963, in which, for the first time, pyrotechnic devices, developed and provided by the Naval Weapons Center (NWC), China Lake, California, were utilized to seed a large continental thunderstorm. This seeding technique made it possible to release at least 6×10^{18} freezing nuclei at cloud base in less than 4 min. Analysis of the data from this case indicates the likelihood of stimulation of convection and a more rapid horizontal growth of the thunderstorm echo following seeding, rather than evidence for dissipation effects from overseeding.

The seeding was conducted approximately 25 miles west southwest of New Raymer, Colorado, radar site. This site was operated and maintained by the Colorado State University Hail Suppression Research Project. Fig. 1 shows the positions of the radar site and the track that the airplane flew during the time of seeding.

2. Weather Patterns

Fig. 2 shows the surface weather pattern for 1100 MST on 26 July 1963. The test case was located behind a cold front that extended from the Northern Plains into Central Colorado. The 500-mb pattern at the time of the test showed a weak westerly flow over Colorado and a weak trough over eastern Colorado. A weak jet stream was located at the 300-mb level north of northwestern Colorado. At test time there was 1 in. of precipitation water in the atmosphere over eastern Colorado. All the above information was obtained from U.S. Weather Bureau synoptic charts. Fig. 3 is the Denver sounding for 0500 MST and shows that the atmosphere was potentially highly unstable.

Fig. 4 shows the 24-hour rainfall amounts in northeastern Colorado for the period ending at 2400 MST. It should be noted that more than 1 in. of rain occurred directly downstream from the location of the seeding, and that rainfall amounts in excess of 4 in. occurred during this 24-hr period. The Sterling, Colorado, Weather Bureau observer officially reported 2.56 in. of rain during this same period. An analysis of the yearly extreme rainfall amounts at Sterling indicates that for the period of record, 1937 through 1964, rainfall amounts exceeding 2.56 in. occurred on only 1 day. The frequency of occurrence of 2.56 in. is approximately once in 12 years as determined using Gumbel's (1958) extreme probability technique.

3. Silver iodide seeding procedure

The materials used for seeding the thunderstorm were five CY-21

Alecto units, developed by NWC. These are small, enclosed rocket motors employing a polybutadiene fuel oxidized by silver iodate and containing a small amount of aluminum powder. The smoke produced is primarily silver iodide with lesser amounts of aluminum oxide and potassium iodide, and oxides of nitrogen, carbon diodide, and some free silver and iodine.

The units were mounted and burned nozzle downward beneath the wing of a Cessna aircraft. (Fig. 5) The material was ejected in excess of sonic velocity and then swept away by the wind; hence, it is likely that smaller particles were produced than would be the case in a wind-tunnel test.

The temperature dependence curve is shown in Fig. 6. It is important for our purposes that a relatively large number of freezing nuclei are available at the warmer temperatures, from -5 to -12C. These nuclei also serve as very active condensation nuclei in all parts of the cloud warmer than -5C.

Because the nuclei were released at temperatures above freezing and were swept upward into the active cloud, they probably were all functioning as condensation nuclei and, with the exception of only the very smallest, say $D < 300A$, probably were imbedded or produced droplets that developed into snow crystals as they ascended. The effect of adding droplets to the warmer regions of the cloud must have been significant but is difficult to assess.

The decrease in effectiveness indicated in Fig. 6 at temperatures below -12C would not be important in this application because already formed snow crystals would be wafted aloft, and these would react readily with the vapor phase at those temperatures even if the nuclei did not. The overall effect of the inoculation would be to increase the number of droplets in the lower portions of the cloud with some heating due to condensation, changes in the droplet size spectrum of the lower seeded part, and possibly increased precipitation. The colder parts of the cloud would be warmed by the formation of ice, utilizing the heat of condensation and heat of fusion as well, with subsequent lowering of the water vapor pressure in the seeded portion of the cloud. At first, the updrafts would have been increased, perhaps changing the dynamic pattern of the cloud and introducing more moisture from below followed by further condensation and freezing. Secondarily, increased rainfall brought about by condensation produced by the increased uplift probably played an important part in the reaction of the cloud.

It is interesting to compare the number of nuclei produced by the acetone burner system. At -20C the Lohse burners used at Colorado State University in 1964-65 produce 10^{15} nuclei per gram of silver iodide. One of these generators can produce 7×10^{15} nuclei per min. An Alecto produces about an equal number of nuclei per gram of silver iodide at -20C and releases about 1.2×10^{3} grams in 45 sec; five units burned sequentially release 7×10^{18} nuclei effective at -20C, 7×10^{17} nuclei effective at -12C, and 5×10^{14} nuclei effective at -5C. The difference

at -5C is truly phenomenal because the acetone generator is completely ineffective at that temperature for smoke introduced below the cloud, due to the very small average particle size characteristic of such generators and to the fact that the silver iodide-alkali iodide smoke is water soluble, and the characteristics in a cloud regime would differ markedly from those found in a cold box.

Thus at -20C the same effect would have required some 1,000 min of acetone generator seeding, at -12C about 100 min, and at -5C almost an infinite period of operation. At -14C the two systems would be about equivalent except that when the nuclei were introduced from below and carried to altitude as ice crystals, the total effect of the Alecto seeding would be many orders of magnitude better than an equivalent seeding time by an acetone generator, because the solubility of the silver iodide-alkali iodide smoke would result in droplets that would not freeze until temperatures of the order of -10C were reached.

Considering the lifetime of a cloud, the rate at which the physical processes are going on, and the magnitude of the entire system, it is reasonable to consider the Alecto-type "shock treatment" as being an effective means of disrupting the dynamics of a large cloud. This high seeding rate is many times the highest rate usually employed, and the seeding took place so rapidly with respect to the lifetime of the storm that the dynamic effects produced by the seeding must have been more than would have been realized by ordinary seeding methods. Perhaps the most important consideration here is the amount of material released in a very short period of time relative to the lifetime of the storm in question.

4. Results

Analysis of the plan position indicator (PPI) radar film of this test indicates a marked horizontal growth in echo from the place and following the time of seeding. Subsequent to seeding, the echo was too close to New Raymer to obtain accurate measurements of the height of the cloud tops. Fig. 7 shows the position of the storm, at 5-min intervals, relative to the radar, the increase in echo area during the 35-minute period during and after seeding, and the track of the seeding aircraft relative to both the radar and the storm and radar range marks at 20-n. mi. intervals.

5. Interpretation

A primary problem in the analysis of these data is to determine whether this rapid growth of the test storm, as indicated by the rapid growth of the radar echo, was an event that could be attributed to the seeding.

From the data of Fig. 7, the rate of advance of the radar echo was determined. Fig. 8 illustrates this, showing the rate of advance of the northern edge of the echo at 10-min intervals, from the time seeding began, and shows speed in excess of 90 knots. The maximum speed of the horizontal growth as measured across the largest diameter

(not shown in Fig. 8) was 104 knots for the 10-min period ending at 1547 MST. The diameter was measured along a north-south line.

Fig. 9 shows the area of the radar echoes from the seeded cloud and from three other cloud echoes present at the same time on the radar scope. The volume of the clouds may not be directly inferred because of lack of height data, but was much greater for the seeded cloud because of the greater vertical growth.

The rapid rate of horizontal growth of the seeded echo was surprising, particularly in view of the fact that the maximum reported wind from the Denver sounding (Fig. 3) did not exceed 30 knots. A similar effect was observed by Malkus and Simpson (1964) in a series of experiments in the Caribbean in which much smaller maritime clouds were seeded with as many as 20 of the same type of Alecto units, dropped vertically through the clouds. Kraus and Squires (1947) suggest a mechanism which holds possibilities in both cases.

It was considered appropriate to make comparisons with other cases in order to determine the probability of occurrence of this behavior. Four types of comparisons were made, over 10-min intervals, and were as follows:

1. Other echoes occurring on 26 July 1963. From the available film taken of the New Raymer radar scope on 26 July 1963, there were four cloud groups visible. The maximum growth rate observed on the remaining three groups was 28 knots.

2. Other echoes associated with rainfall amounts in excess of 2 in. for which radar data were available during 1964 and earlier years. Other echoes were examined which were associated with 24-hr rainfall amounts in excess of 2 in. The maximum growth rate for the other six cases available for study was 62 knots.

3. All other test cases not seeded that were compiled for a previous publication. Test cases which were not seeded (1962-1964) have been compiled in a report by Schleusener and Sand (1964) summarizing data from the test cases. Fig. 10 shows a Gumbel plot of the speed of echo advance in these cases and the 1965 no-seed cases. This chart shows a recurrence interval of 104-knot horizontal growth speed to be approximately 350 "test case days", which corresponds roughly to once in 35 years.

4. Maximum speeds of advance of all unseeded radar echoes within each of the four 15-day periods from 1 June to 31 July for the years 1961-1965. The recurrence interval of the 104-knot speed by this analysis is approximately 4 years. This recurrence interval is reduced by the occurrence of one 100-knot event (17 July 1962). There is a strong indication that this 100-knot growth rate may not be a true growth rate, but may have been caused by attenuation. There is no evidence of attentuation on the 26 July 1963 case.

6. Conclusions

From analysis of these data it is concluded that the probability is high that the rapid horizontal growth of the test case cloud, as indicated by photographs of the PPI radar scope, was influenced by seeding with the pyrotechnically produced silver iodide. Whether or not the seeding was influential in increasing rainfall or was effective in suppressing the formation of hail cannot be verified either positively or negatively at this stage.

7. Additional comments

On 7 July 1966, another large thunderstorm was seeded, again with five Alecto units, over Rapid City, South Dakota. This seeding effort was associated with Project Hailswath, a special National Science Foundation project designed to concentrate a large number of people on the hail and hail suppression problem.

The five Alectos were fired within a 10-min period, below cloud base, on an east-west track from the eastern edge to about the center of the storm, and lying nearly equidistant between the north-south edges of the storm.

Unfortunately, time-lapse photographs of the radar are not available, but two-hand drawn overlays of the radar echo were made; one when seeding began and the second 28 min after seeding.

Based on the limited data available, growth rates of the radar echoes (toward the east) were estimated to be in excess of 90 mph, even when considering a general eastward cell movement of 3 n. mi.

Fig. 11 shows a composite of the data available from this storm. This case is of interest in that the rapid growth rates from the seeding case of 26 July 1963 appear to be repeated in the 7 July 1966 case.

Further tests are desirable to determine whether the effects that appear to have been produced in these two cases can be accomplished repeatedly, and to further evaluate the effects of such seeding on storm growth and precipitation.

Thus, even though no conclusions can be drawn at this time on this case, it seems appropriate to mention it here if for no other reason than the fact that it was the second large Great Plains thunderstorm to be seeded with five Alecto units, the first being the primary topic of this paper.

Hopefully, further study will uncover more useful data.

ACKNOWLEDGMENTS

The facilities of the Colorado State University hail reporting network were supported by the Atmospheric Science Program, National Science Foundation Grant NSF G23706.

The Alecto pyrotechnic seeding devices were provided by the U.S. Naval Ordnance Test Station, China Lake, California.

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4. Kraus, E.B. and P. Squires, 1947, "Experiments on the stimulation of clouds to produce rain," Nature, 4041.

5. Schleusener, R.A., and Wayne Sand, "Summary of data from test cases of seeding thunderstorms with silver iodide in northeastern Colorado, 1962-63-64." Progress Report, NSF GP 2594, Civil Engineering Section, Colorado State University, Fort Collins, Colorado, CER64RAS35, 1964.

CASE STUDY OF APPARENT STIMULATION OF
CONVECTION BY SEEDING A THUNDERSTORM
WITH "ALECTO" PYROTECHNIC DEVICES

FIGURE LEGENDS

FIG. 1. Position of Radar Site and Aircraft Seeding Track.

FIG. 2. Surface Weather Pattern, 1100 MST, 26 July 1963. X in dotted area shows location of test case.

FIG. 3. Denver Sounding 0500 MST, 26 July 1963 (skew-T log p diagram).

FIG. 4. Twenty-four-hr Rainfall, Northeastern Colorado, for Period ending 2400 MST 26 July 1963.

FIG. 5. Electro Motor Being Burned Beneath the Wing of a Cessna Aircraft, Seeding the Updraft of the Cloud in Question. The Smoke is Being Emitted in Excess of Sonic Velocity.

FIG. 6. Silver Iodide Efficiency Curves, Nuclei Vs. Temperature.

FIG. 7. Diagrams Showing Change in Radar Echo, Seeding Track and 20-n mi. Range Markers, at 5-min Intervals From 1525 to 1600.

FIG. 8. Growth Rate of Northern Edge of Echo in 10-Min Intervals.

FIG. 9. Area of Seeded Cloud and Adjacent Clouds as a Function of Time.

FIG. 10. (a) Gumbel Plot, 26 July and 1964-1965 No-Seed Cases.
(b) Gumbel Plot - Maximum Growth Rates, 15-day periods 1961-1965 and 26 July 1963.

FIG. 11. Seeding and Rainfall Data from 7 July 1966 Storm (Project Hailswath).

FIGURE 1

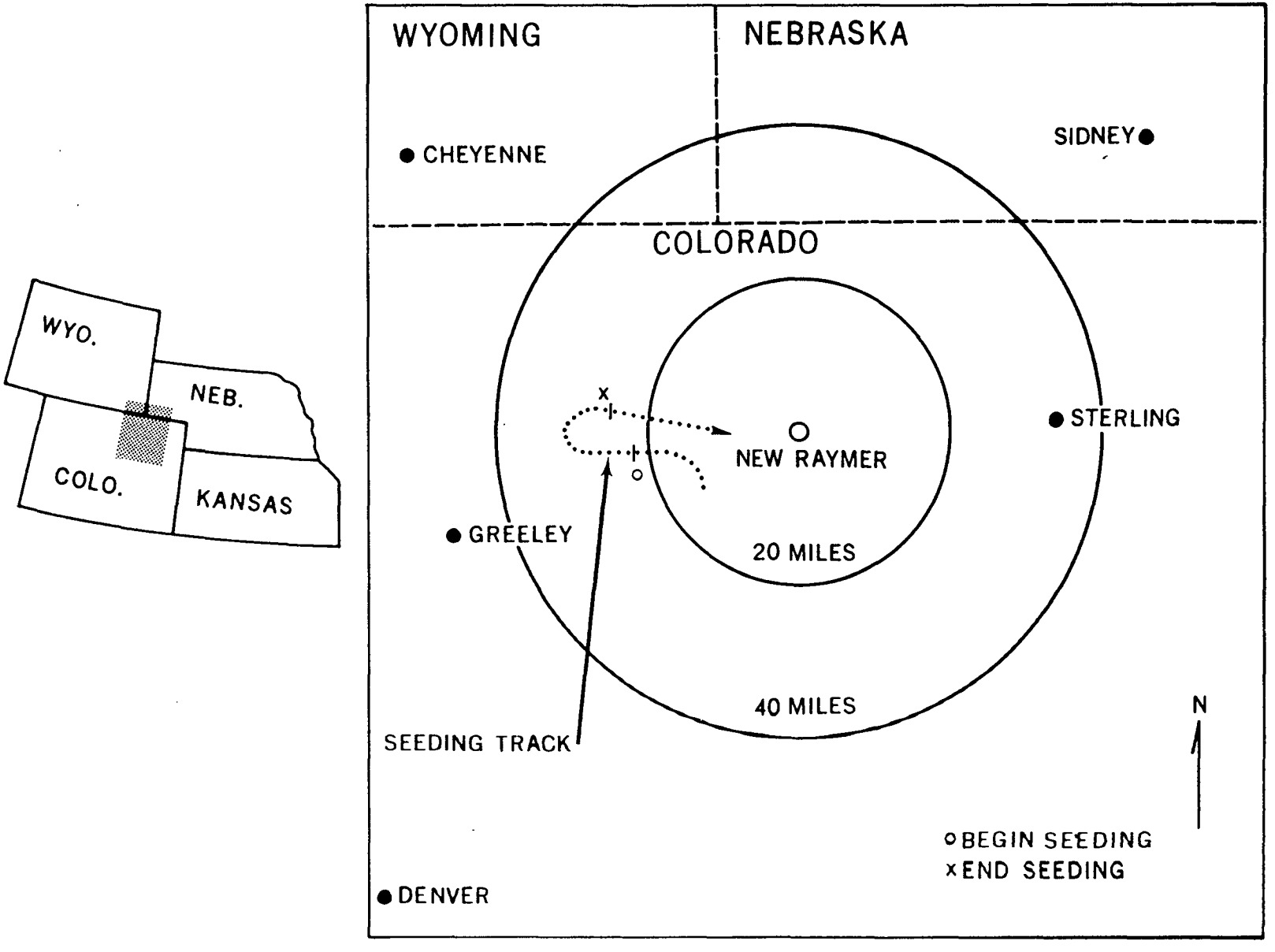
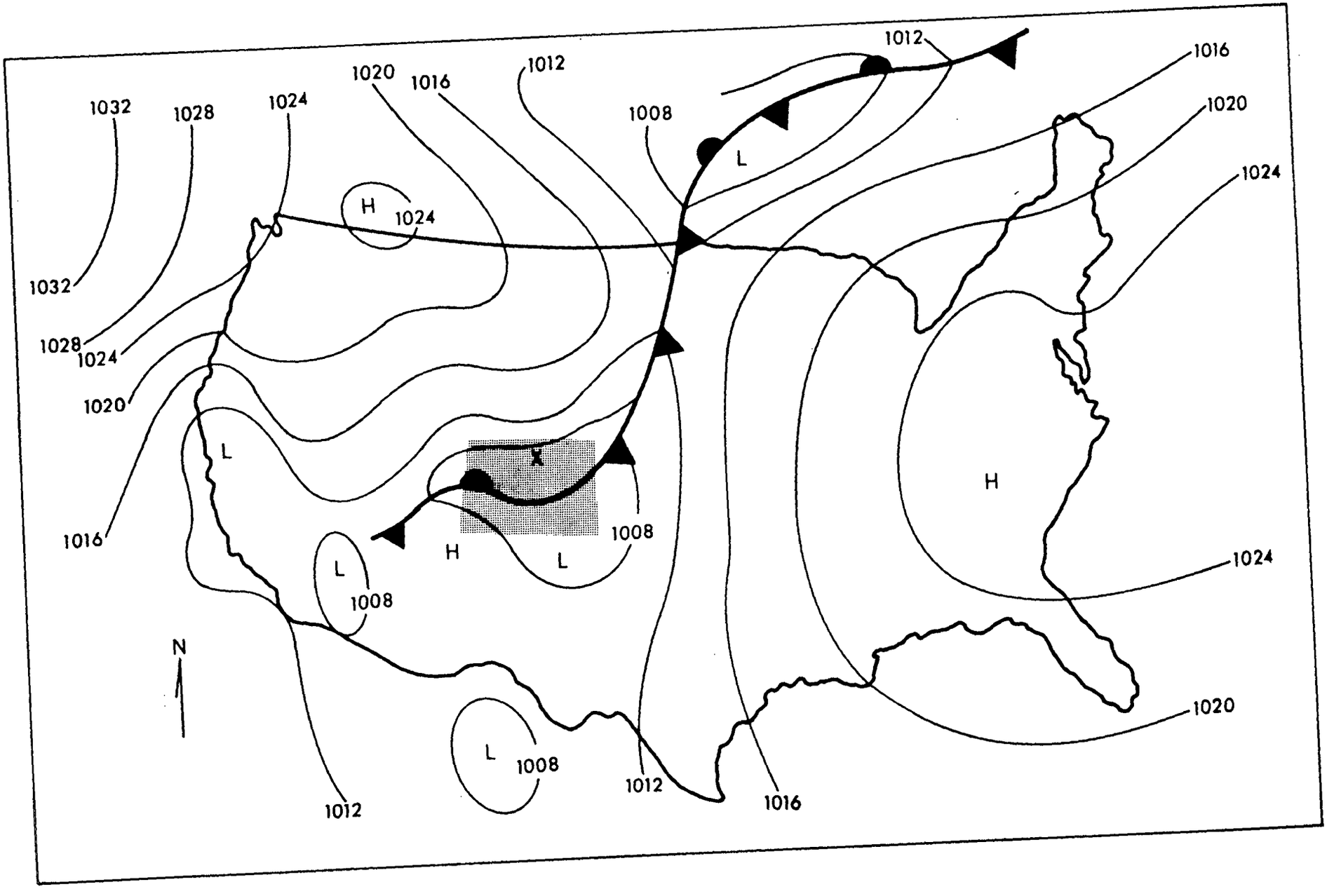

WYOMING
NEBRASKA
CHEYENNE
SIDNEY
COLORADO
WYO.
NEB.
COLO.
KANSAS
NEW RAYMER
STERLING
GREELEY
20 MILES
40 MILES
SEEDING TRACK
N
BEGIN SEEDING
END SEEDING
DENVER

FIGURE 2


1012
1016
1020
1016
1012
1008
1032
1028
1024
1024
L
H
1024
1024
1032
1028
1024
1020
1016
L
X
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1024
1020
N
L
1008
1012
1012
1016

FIGURE 3

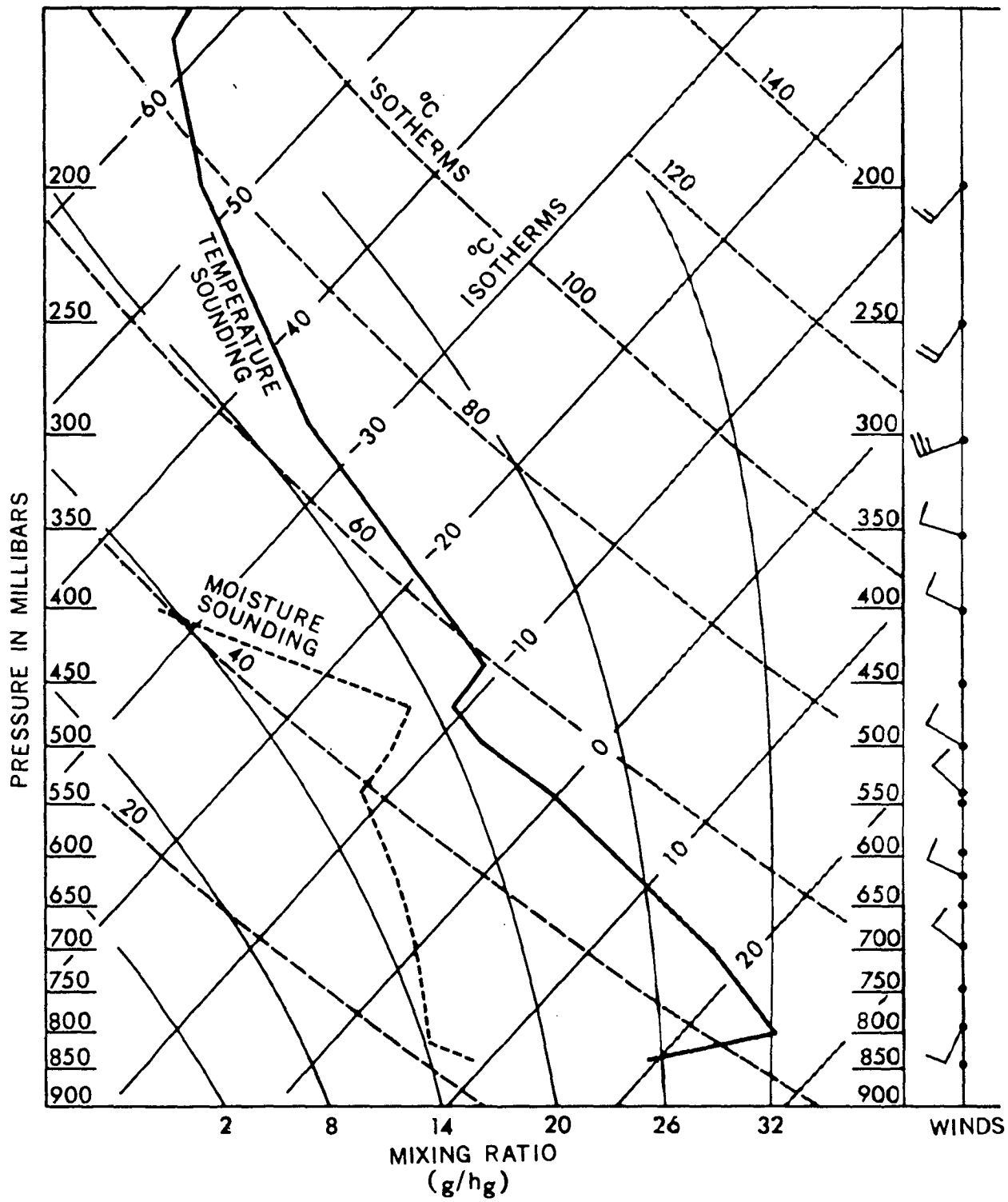
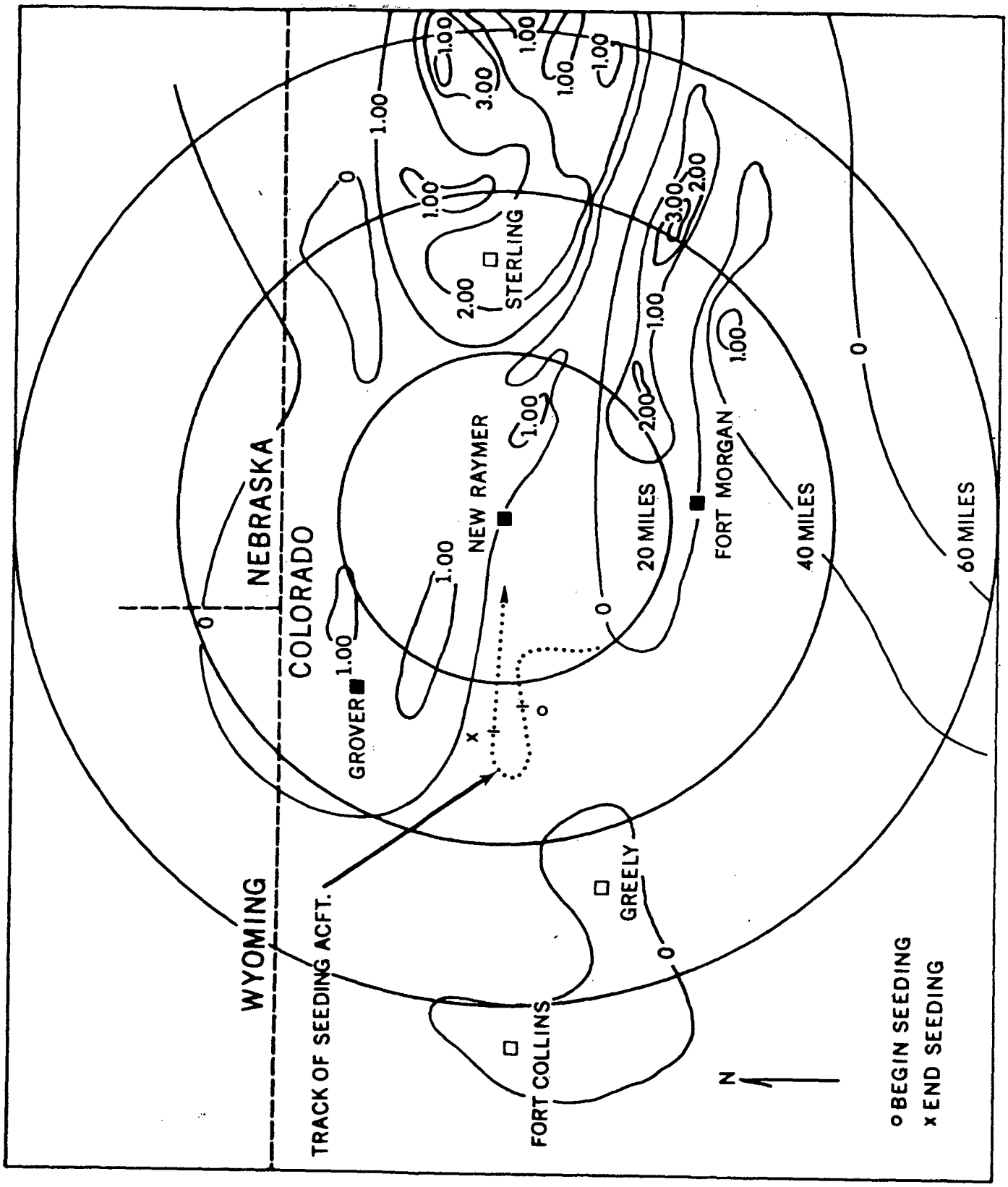

°C ISOTHERMS
°C ISOTHERMS
TEMPERATURE SOUNDING
MOISTURE SOUNDING
PRESSURE IN MILLIBARS
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
2
8
14
20
26
32
MIXING RATIO (g/hg)
WINDS

FIGURE 4


WYOMING
NEBRASKA
COLORADO
TRACK OF SEEDING ACFT.
GROVER
NEW RAYMER
STERLING
FORT COLLINS
GREELY
FORT MORGAN
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40 MILES
60 MILES
N
o BEGIN SEEDING
x END SEEDING
0
1.00
2.00
3.00

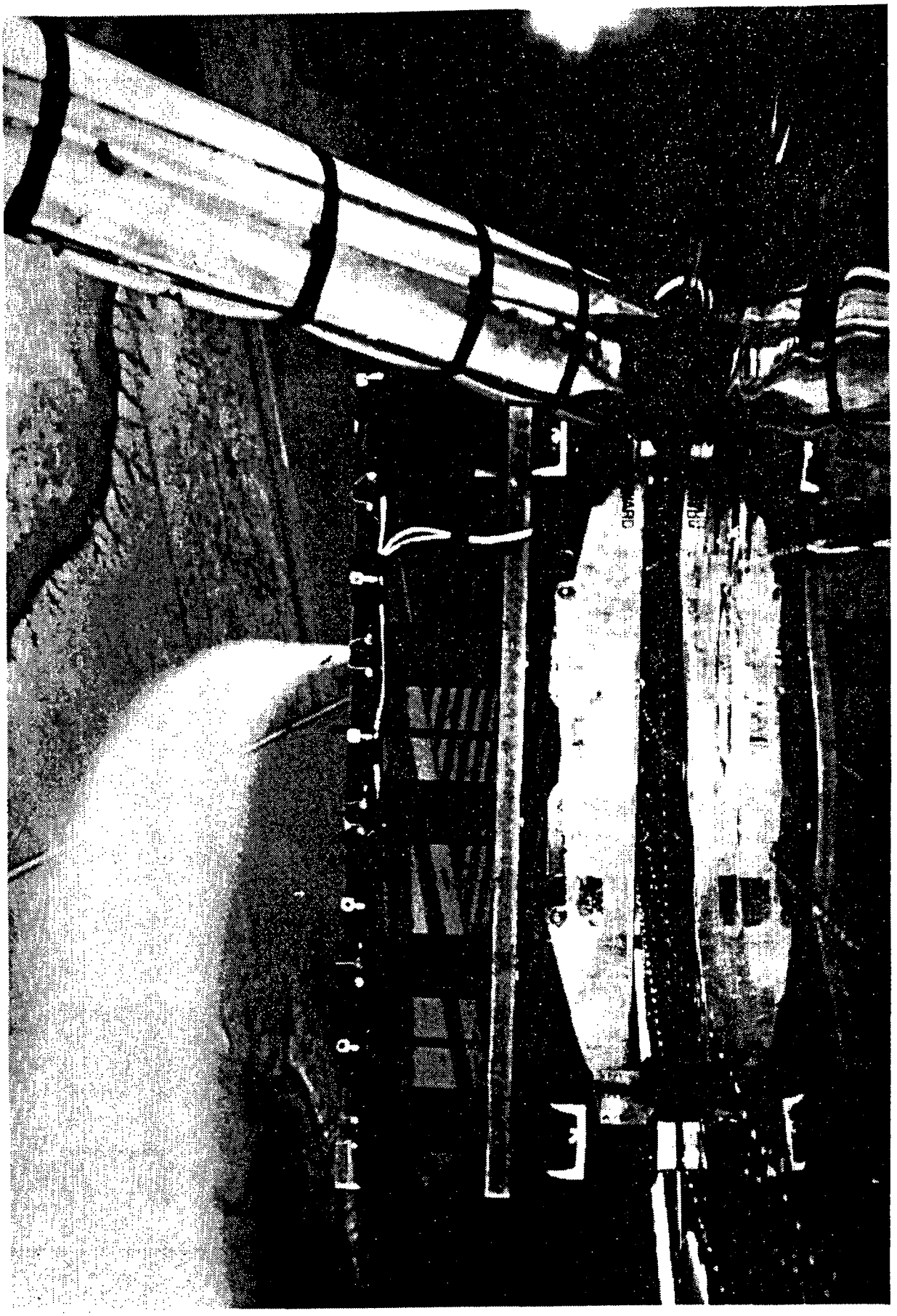


FIGURE 5

FIGURE 6

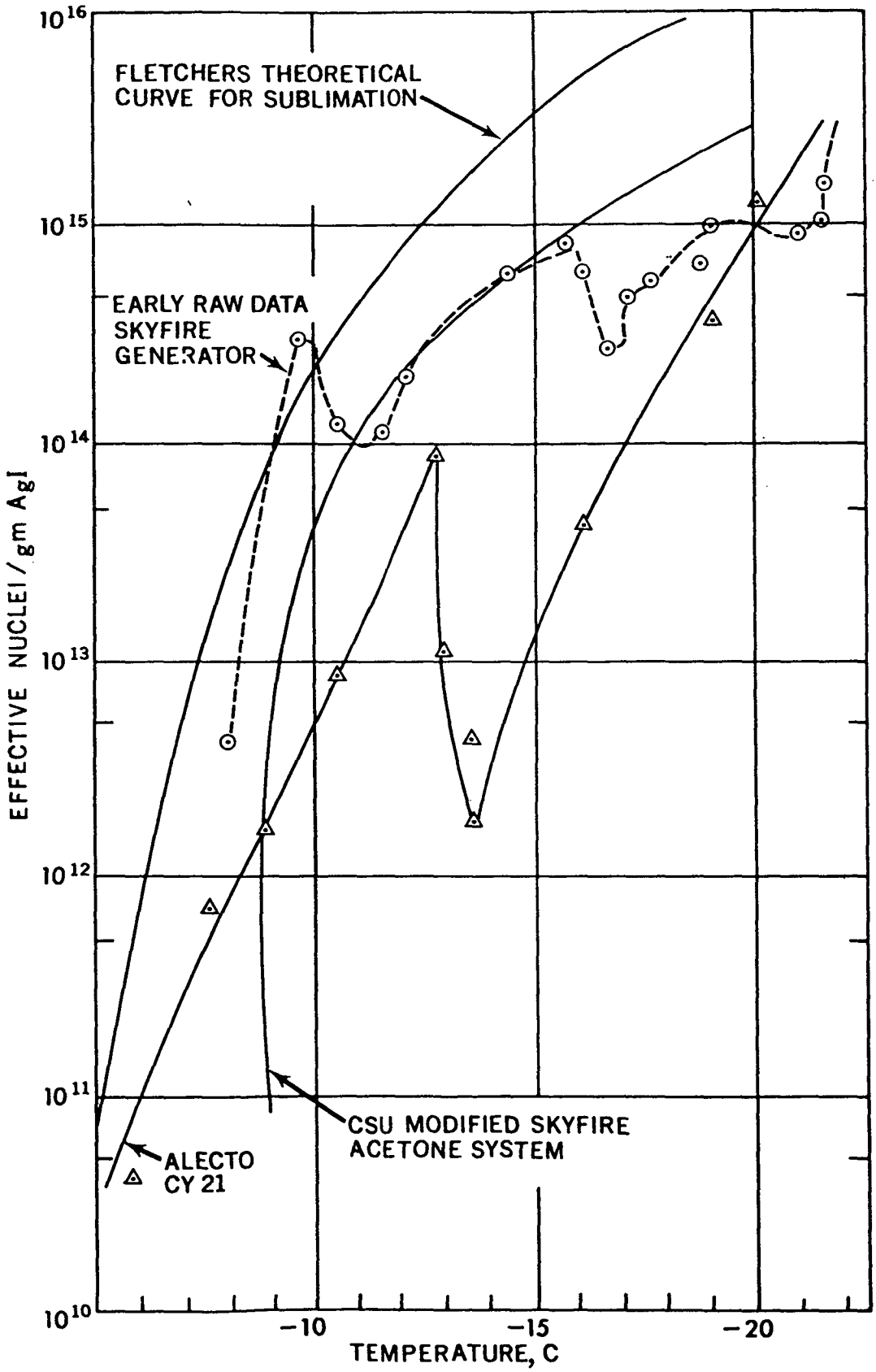
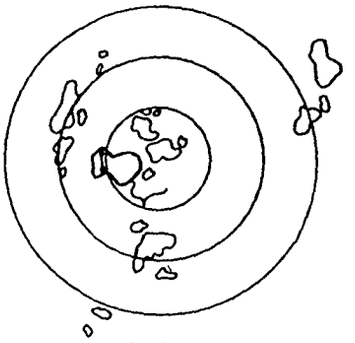
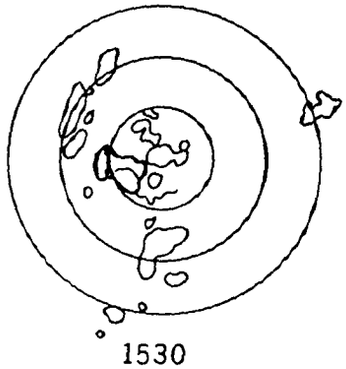

FLETCHERS THEORETICAL CURVE FOR SUBLIMATION
EARLY RAW DATA SKYFIRE GENERATOR
CSU MODIFIED SKYFIRE ACETONE SYSTEM
ALECTO CY 21
EFFECTIVE NUCLEI / gm AgI
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
−10
−15
−20
TEMPERATURE, C

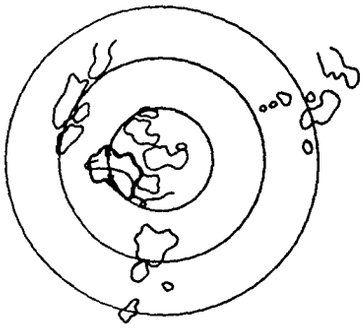
FIGURE 7



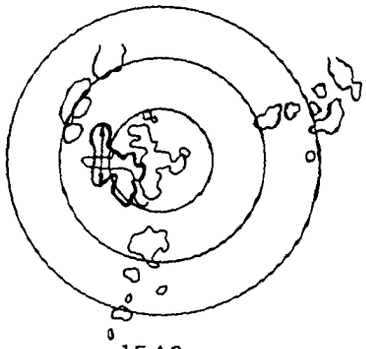
1525
S-4



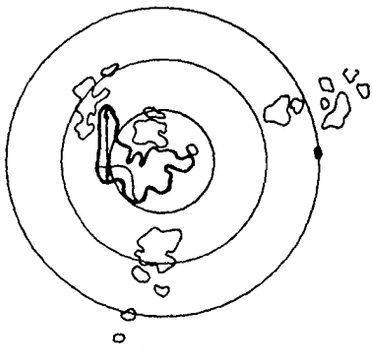
1530
S+1



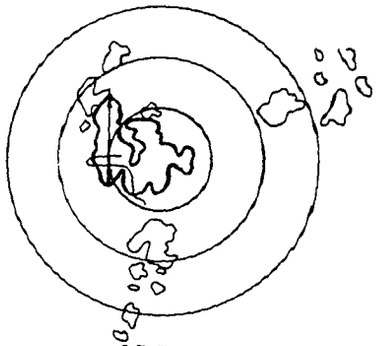
1535
S+6



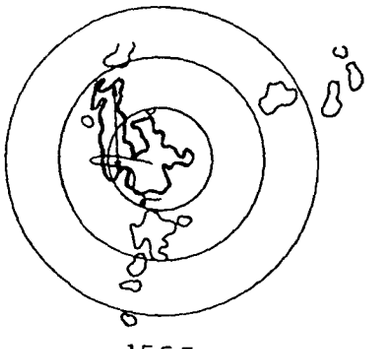
1540
S+11



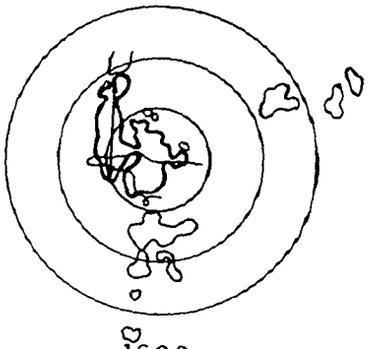
1545
S+16



1550
S+21



1555
S+26



1600
S+31

FIGURE 8

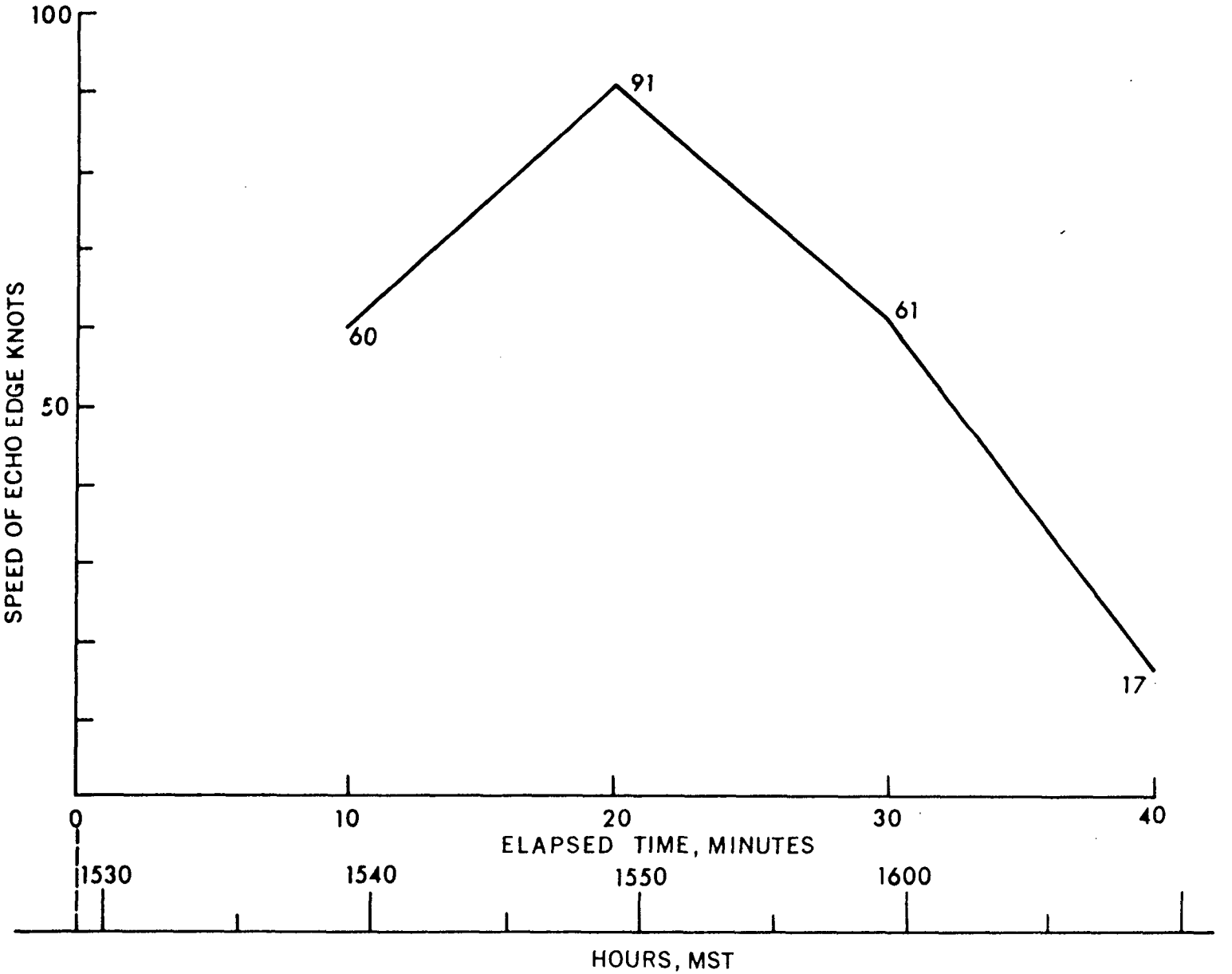

100
50
SPEED OF ECHO EDGE KNOTS
91
60
61
17
0
10
20
30
40
ELAPSED TIME, MINUTES
1530
1540
1550
1600
HOURS, MST

FIGURE 9

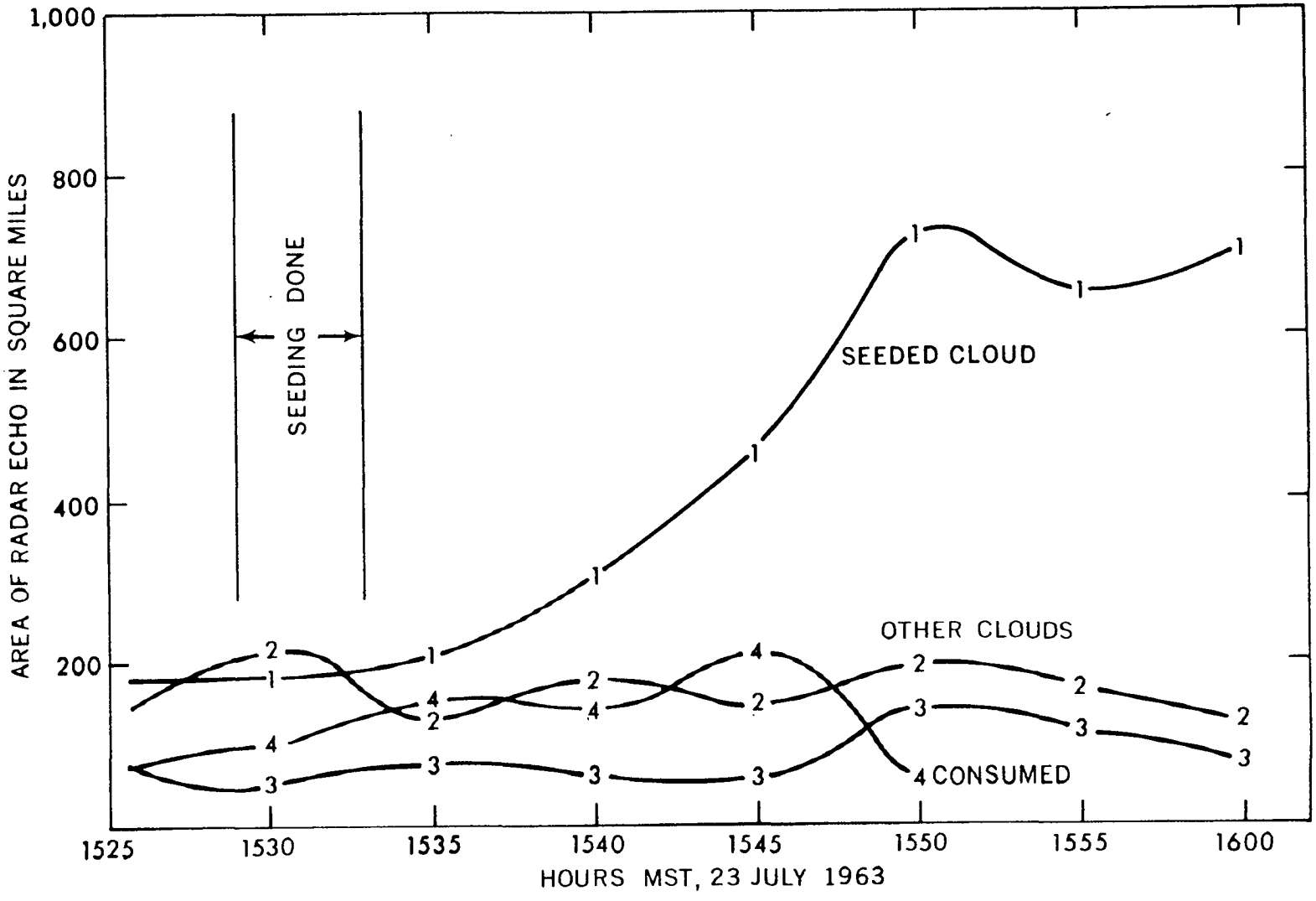

1,000
800
600
400
200
AREA OF RADAR ECHO IN SQUARE MILES
SEEDING DONE
SEEDED CLOUD
OTHER CLOUDS
CONSUMED
1525
1530
1535
1540
1545
1550
1555
1600
HOURS MST, 23 JULY 1963

FIGURE 10 (a)

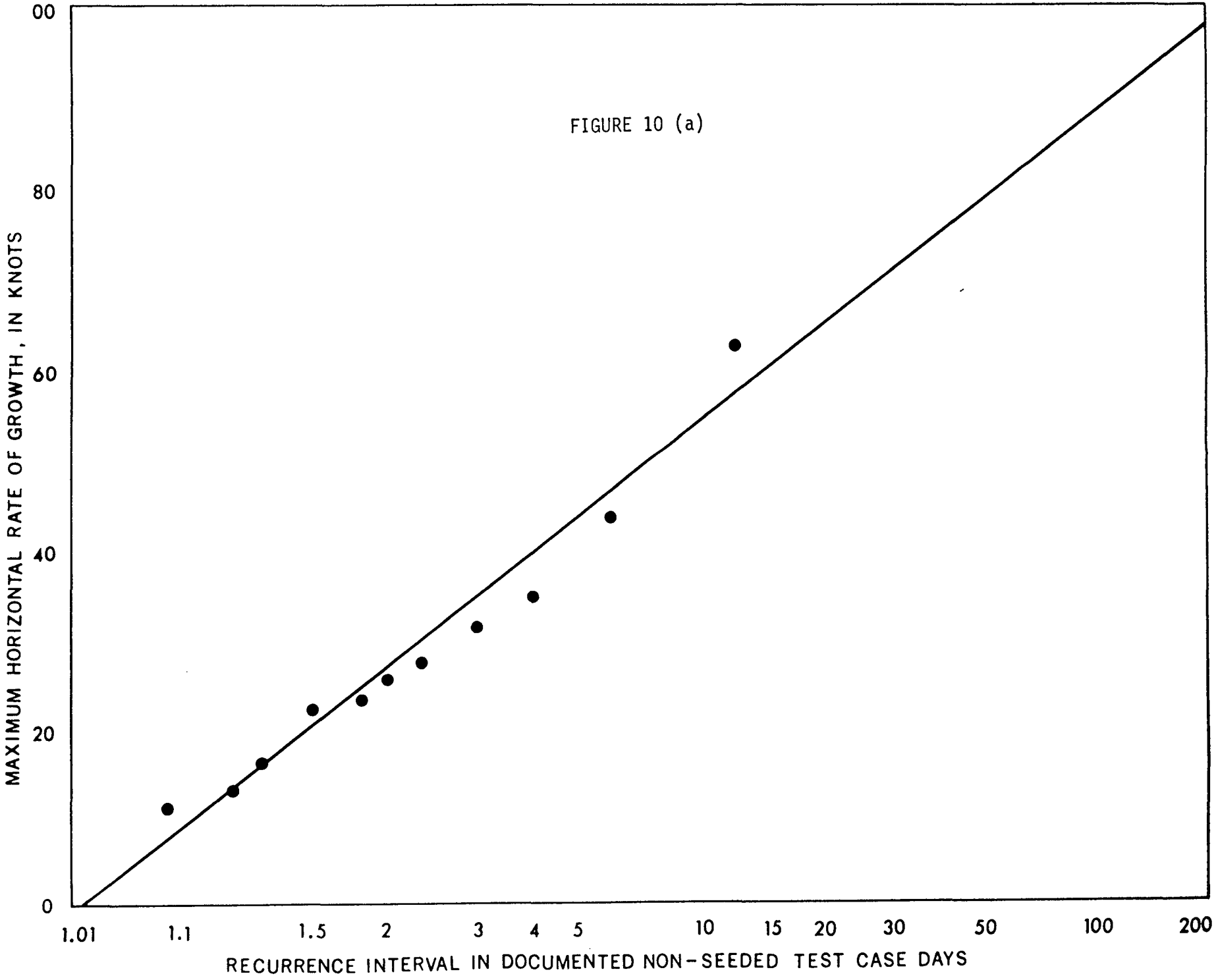
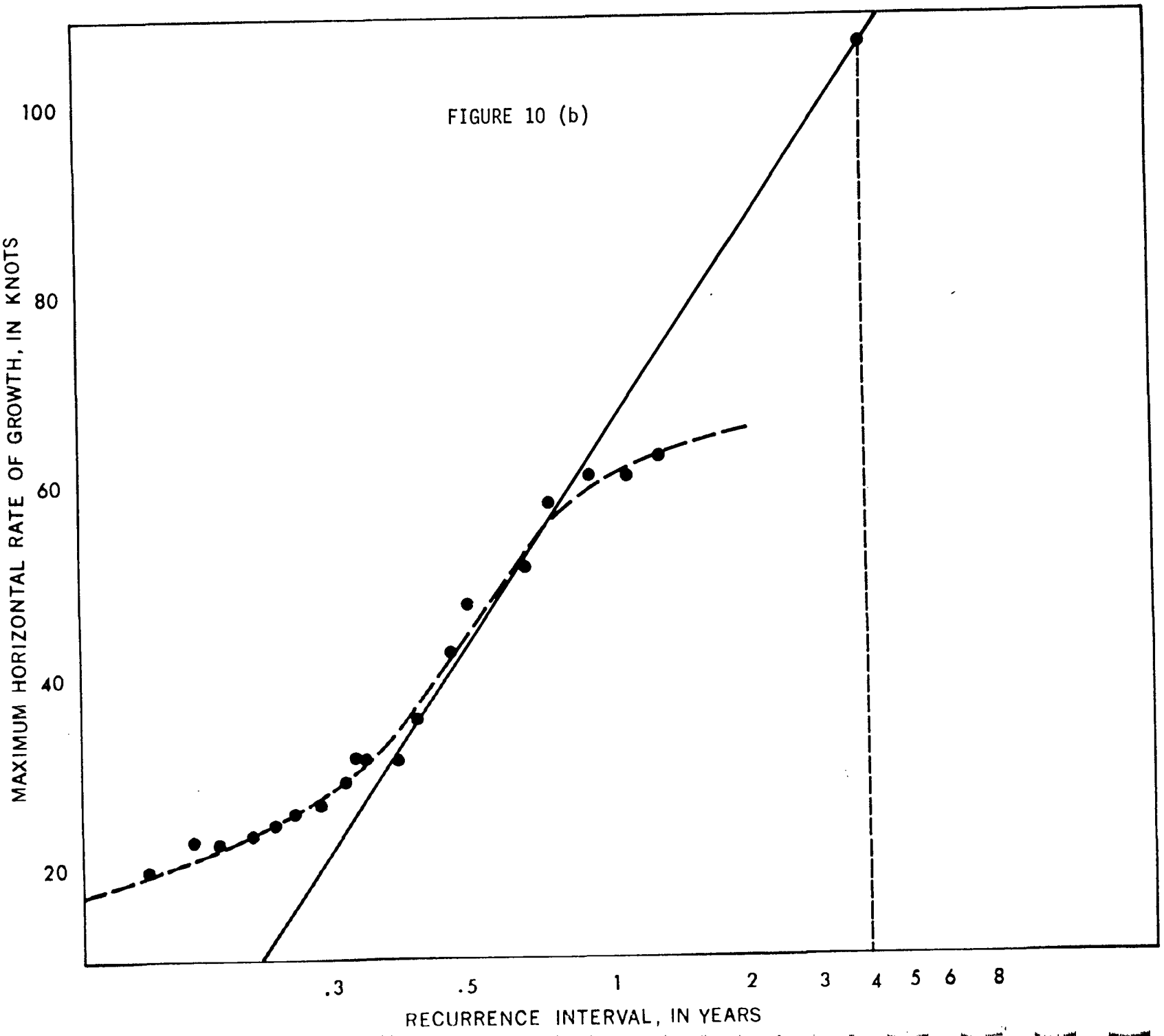
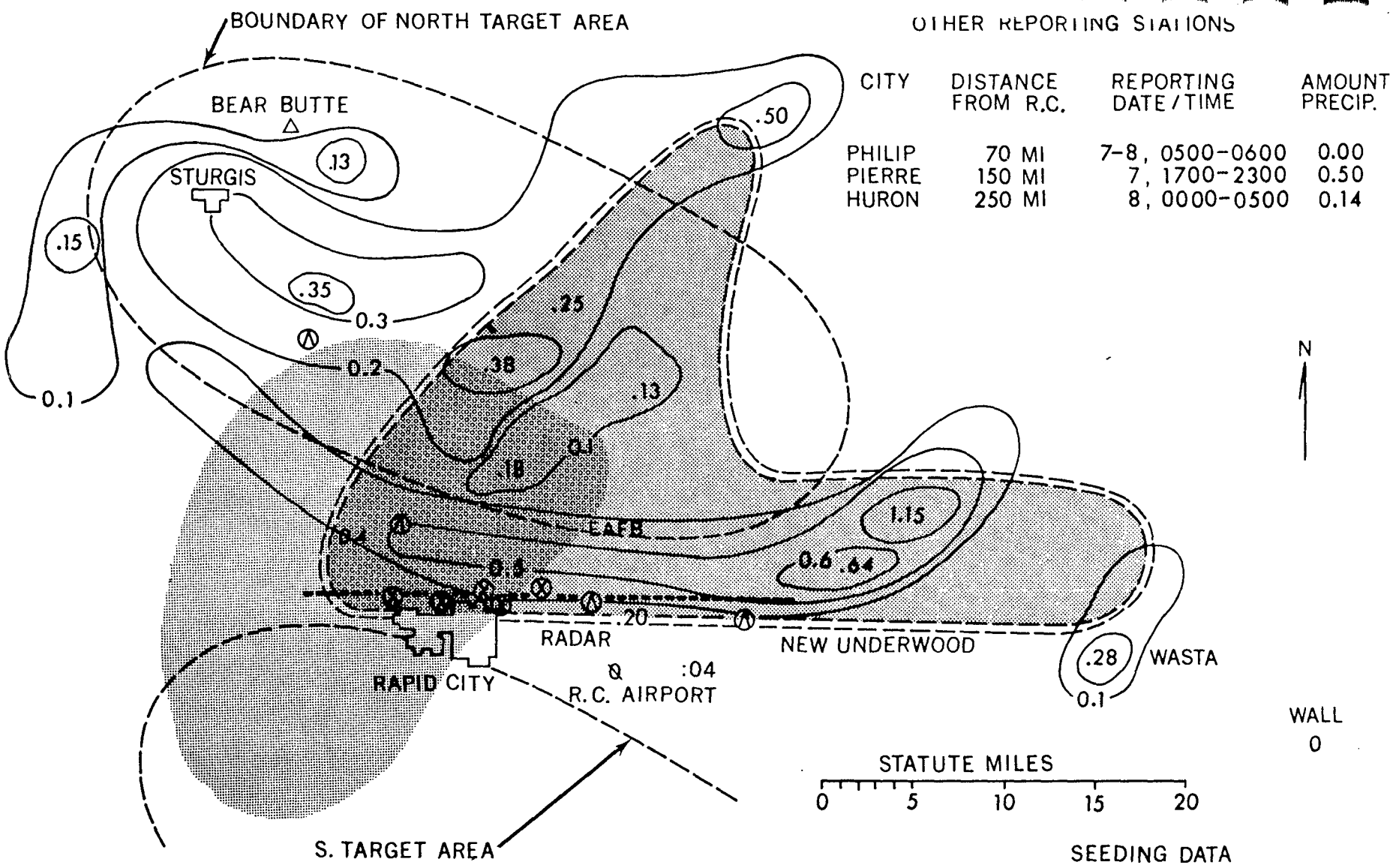

00
80
60
40
20
0
MAXIMUM HORIZONTAL RATE OF GROWTH, IN KNOTS
1.01
1.1
1.5
2
3
4
5
10
15
20
30
50
100
200
RECURRENCE INTERVAL IN DOCUMENTED NON-SEEDED TEST CASE DAYS

FIGURE 10 (b)


MAXIMUM HORIZONTAL RATE OF GROWTH, IN KNOTS
100
80
60
40
20
.3
.5
1
2
3
4
5
6
8
RECURRENCE INTERVAL, IN YEARS



OTHER REPORTING STATIONS

CITY	DISTANCE FROM R.C.	REPORTING DATE/TIME	AMOUNT PRECIP.
PHILIP	70 MI	7-8, 0500-0600	0.00
PIERRE	150 MI	7, 1700-2300	0.50
HURON	250 MI	8, 0000-0500	0.14

SEEDING DATA

AIRBORNE ACETONE GENERATORS ON 1621, OFF 1706

ALECTOS FIRED AT 1637, 1638, 1644, 1645, 1646

OLIN FLARES IGNITED AT 1708, 1720

FIGURE 11

SOME OBSERVATIONS OF SILVER IODIDE PLUMES WITHIN THE ELK MOUNTAIN WATER RESOURCE OBSERVATORY

by

August H. Auer, Jr.
Donald L. Veal
and
John D. Marwitz

Natural Resources Research Institute
College of Engineering
University of Wyoming
Laramie, Wyoming

ABSTRACT

During the 1966-68 winter seasons, plume tracking studies were conducted within the Elk Mountain Water Resource Observatory. These studies conducted at the University of Wyoming's Elk Mountain research facility indicated that the silver iodide plume did not mix to vertical depths greater than about 450 meters and that the angle of dispersion was usually about 10 degrees. An inverse relationship between lapse rate and diffusion angle was established using previously published data along with data collected during this research. Concentrations of ice nuclei found within the seeding plume at the Observatory some 10-17 km downstream from the release point varied from a few nuclei per liter at the edges of the plume to a maximum concentration of about 150 per liter active at -20C.

1. INTRODUCTION

Many attempts have been made to increase precipitation or suppress hail by releasing ice nuclei in the form of silver iodide smoke from ground-based generators in the hope that the nuclei will find their way into supercooled water clouds, and thus initiate precipitation by the Bergeron ice crystal process. However, it has not yet been established what volume of the cloud is affected or what concentration of artificial ice nuclei results within the treated cloud (Smith and Heffernan, 1967).

The purpose of this paper, therefore, is to present some observations of silver iodide plume dimensions which were obtained within the Elk Mountain research facility of the University of Wyoming.

II. PROCEDURES

The ice nuclei data used in this paper were obtained by two NCAR ice nucleus counters; one in the Observatory atop Elk Mountain and the other in the University of Wyoming aircraft.

Information relating to the operation of the NCAR ice nucleus counter may be found in Langer, et al. (1967); Steele, et al. (1967); and Auer and Veal (1968).

Plume measurements were obtained during the winter months within the Elk Mountain Water Resource Observatory. During these studies, the silver iodide generator was typically operated at a distance of 9-17 km upstream from the location of the NCAR counter atop Elk Mountain. By positioning the silver iodide generator at various locations on the seeding road, (see Fig. 1) very small lateral displacement of the generator source could be achieved. In this study, the silver iodide plume was defined as any volume of atmosphere in which the ice nucleus concentration exceeded the background values by one order of magnitude (i.e., 10 nuclei liter^{-1} at -20C would be considered the plume boundary if the ambient concentration was 1 nucleus liter^{-1} at -20C). In order to obtain an estimate of the plume width, it was assumed that the physical shape of the plume remained somewhat constant with time and for small movements of the seeding source. Based on these assumptions then and making small lateral displacements of the generator source and detecting the changing concentrations of the nuclei at the Observatory, the approximate plume width could be inferred. In addition, during such experiments, the aircraft was flown at various positions between the silver iodide dispensing point and the Observatory atop Elk Mountain to establish the location of the plume. Also during these experiments, the temperature lapse rate between the seeding dispensing point and the top of the mountain was continuously monitored. Numerous constant volume balloons and standard meteorological balloons were released during the experiments to determine the wind flow at all levels on the windward side of Elk Mountain.

III. RESULTS

Table 1 summarizes the silver iodide plume tracking activities in the vicinity of Elk Mountain for the 1966-68 seasons. For easy comparisons, all distances between the generator and the ice nucleus counter were standardized at 10 km; during the course of the experiments, the distance varied between 9 and 17 km. This standardization was accomplished by plotting the plume dispersion between the source and the Observatory (point where the width was detected) and then simply measuring the plume width at the 10 km position. All the plume tracking experiments were conducted on cloudless days; however, the presence of the cap cloud on Elk Mountain is accompanied by the same dynamic and stability conditions as were present during these tests. It can be seen from Table 1 that for a distance of 10 km downwind from the generator, the plume width varied between 1.0 and 3.7 km. The horizontal angle of

UNIVERSITY OF WYOMING
NATURAL RESOURCES RESEARCH INSTITUTE
ELK MOUNTAIN WATER RESOURCES OBSERVATORY
CONTOUR INTERVAL 1000 FEET
INSTRUMENT SITE
SEEDING GENERATOR POSITION
ROAD
STREAM
SCALE (Miles)
SCALE (Kilometers)
N
Radar
Brush
Schooler Saddle Observatory
Southwest
Jack Cr.
Mid Cr.
Snyder County
ELK MTN 11156
Cheesebrough
McKee Ranch
ER Ranch (Texas)
COLD MTN 9504
PENNOCK MTN 9968
8628
7000
8000
9000
10000

dispersion of the seeding nuclei from the generator was calculated to be between 8.0 degrees and 21.0 degrees. Also listed in Table 1 are the mean wind speeds within the layer 450 m above the prevailing terrain, and the existing lapse rate measured from the base of the mountain to the Observatory.

TABLE 1

A summary of the AgI plume measurements from Elk Mountain, Wyoming at a distance of 10 km downstream from the generator. The data includes dates of observations, mean wind speed in the layer 450 m above ground level, mean travel speed of the AgI from the generator to the sampling site, the temperature lapse rate, the plume width and the horizontal angle of dispersion.

DATE	MEAN WIND SPEED mps	MEAN TRAVEL SPEED mps	LAPSE RATE C Km^{-1}	PLUME WIDTH km	HORIZONTAL ANGLE OF DISPERSION degrees
9 March 67	16	10	8.4	2.5	12.4
21 March 67	14	14	11.3	1.5	8.2
22 March 67 (a)	14	14	11.3	1.5	9.2
22 March 67 (b)	14	14	11.5	1.6	8.0
23 March 67	15	15	10.6	1.5	8.2
24 March 67	11	6	9.8	1.9	11.1
6 Dec 67	11	6	9.1	2.5	14.2
31 Jan 68	10	6	8.0	2.7	15.4
1 Feb 68	16	13	9.3	1.7	9.8
21 Feb 68	13	6	6.7	1.0	11.5
23 Feb 68	12	8	5.9	2.3	13.2
6 March 68	6	3	6.2	3.7	21.0
13 March 68 (a)	11	5	8.8	1.6	9.2
13 March 68 (b)	21	5	7.3	2.5	14.2
14 March 68	9	6	7.9	2.2	12.6
15 March 68	14	10	8.9	2.0	11.4

Table 2 summarizes data reported by Smith and Heffernan (1956) obtained during studies on the trajectories of silver iodide released from a 1300 m mountain in Australia. In their studies, the travel time of the seeding agent from the generator to a point downstream was not available. Figure 1 presents a curve, utilizing data from both Table 1 and 2, showing the relationship between the temperature lapse rate (abscissa) and the horizontal angle of dispersion (ordinate) of a silver iodide plume at a distance of 10 km downstream from the generator. Also at each data point, the travel speed of the nuclei (whenever available) is plotted above with the mean wind speed in the transport layer.

Superadiabatic lapse rates occasionally occur between the base and top of Elk Mountain and at no time during the plume tracking studies was there any evidence of a temperature inversion between the base and top of the mountain.

TABLE 2

A summary of the AgI plume measurements from Smith and Heffernan (1956) at a distance of 10 km downstream (similarly standardized) from the generator. The data includes dates of observations, mean wind speed in the layer about 450 m above ground level, temperature lapse rate, the plume width, and the computed horizontal angle of dispersion.

DATE	MEAN WIND SPEED mps	LAPSE RATE C Km^{-1}	PLUME WIDTH km	HORIZONTAL ANGLE of DISPERSION, degrees
5 July 53	8	7.3	3.0	17.0
12 July 53	13	7.5	5.0	28.0
17 July 53	10	7.3	3.0	17.0
18 July 53	15	6.9	3.0	16.6
20 July 53	5	8.0	3.0	21.2
24 July 53	6	6.5	5.2	29.0

Willis (1966) conducted diffusion studies with a zinc cadmium sulfide tracer material in the central Rockies. His results, conducted during very stable conditions (22 February 65, lapse rate = 5.5 C km^{-1}, θ = 123.2 degrees; 25 March 65, lapse rate = 4.9 C km^{-1}, θ = 48.8 degrees), indicated extremely wide horizontal dispersion angels. These data are not shown on Figure 1; however, they do not depart significantly from the curve extrapolated from the University of Wyoming and Smith and Heffernan data. Plume dispersion data from two recent examples quoted in Peterson (1968) have also been included in Figure 2.

The curve shown in Figure 2 demonstrates some interesting results. First of all, by examining the mean wind speed plotted at each point, it can be seen that the horizontal dispersion angle of the plume is not as dependent on the speed of the transporting wind but seems to be more closely associated with the value of the temperature lapse rate of the layer of air through which the plume is moving.

With unstable conditions or a superadiabatic lapse rate, the air will rise vertically with both an orographic and dynamic component. The orographic component will increase with increasing terrain slope on the windward side of the mountain while the convective instability is associated with the dynamic component. Qualitatively this suggests that the surface air is mixed vertically more quickly and to a greater

Lapse Rate, C Km⁻¹
5
6
7
8
9
10
11
12
Horizontal Angle of Dispersion, Degrees
6
8
10
12
14
16
18
20
22
24
26
28
30
14/14
15/15
14/14
5/11
13/16
14/14
10/14
6/10
6/13
6/9
8/12
10/16
5/21
6/11
6/10
3/6
University of Wyoming (66-67)
University of Wyoming (67-68)
Smith and Heffernan (1956)
Peterson (1968)

depth within the surface boundary layer or region of maximum mechanical turbulence and thereby has less time to become diffused laterally. Conversely, when stable conditions exist, the dynamic component is essentially zero and the air is lifted only with the orographic component which allows the surface air to remain longer in the region of maximum mechanical turbulence and thereby undergo more lateral diffusion.

Such a circumstance of rapid vertical mixing as discussed above is characteristic of the region in which the studies were accomplished. The material was released over a flat valley plain usually 1.5 to 5.0 km from the beginning of the maximum orographic influence. Thus it seems reasonable that the material would mix vertically near the release point only under unstable conditions.

Results obtained from the Elk Mountain experiments differ from those presented in Pasquill (1962) in which the plume width is proportional to the stability with wider plumes for unstable conditions. The plume dimensions determined by Pasquill were obtained over open, level country with the absence of topographic features and under quite slow surface or transport winds. The results presented in Figure 2 were obtained in mountainous regions with significant interactions with topographic features and under substantial transport winds.

The data shown in Table 1 also suggests that the nuclei are transported at speeds equal to the mean wind (in the layer between the terrain and 450 m above the terrain) under unstable conditions but at a lesser speed during stable conditions. Nuclei being transported under stable conditions do not mix as deep vertically and therefore remain in a position somewhat closer to the ground where the mean velocity is significantly less than the 450 m mean wind. Balloon soundings taken on the windward side of Elk Mountain indicate that the mean wind at about 300 m above the ground is usually from 60 to 70 percent of the 450 m mean wind.

Comparison of the AgI plume direction and speed with analysis of superpressure balloon trajectories indicate that it is the direction and speed (with its dependence upon the stability) of the wind within the layer 450 m above the prevailing terrain that determines the movement of the plume. These results differ with Robertson (1967) who found in the central Colorado Rockies that the wind velocity at the release point is the primary factor in controlling the plume travel for large distances downwind.

At distances greater than 15 km, the concentration of AgI nuclei is observed to depart from what might be called a Gaussian distribution for plumes close to their sources. This is in general agreement with Braham et al. (1952) who reported that symmetrical structures of particle concentrations at distances greater than about 12 km were replaced by more diffuse structures having minor spurts of comparitively high concentration dispersed at random through the plume. Langer et al. (1967), during plume tracking studies in the Central Rockies, reported

that only weak remnants of the AgI plume from ground-based generators could be found at distances beyond 25 km.

Studies on the vertical diffusion of AgI nuclei during orographic seeding situations are very limited. Henderson (1965), using data from the winter seasons of 1962-64 in California's southern Sierras commented on vertical diffusion, though he makes no mention to terrain features or temperature lapse rate. Henderson concluded by saying that it would be risky to make assumptions about the distribution of AgI plumes if the field program were dependent upon the material reaching a given area at a particular time and in a certain concentration. Langer et al. (1967) in Colorado's North Park confirms Henderson's findings and adds that no indication was found in a few tests that the ground-based AgI generators formed plumes consisting of a reasonable number of nuclei that rose above the terrain more than 450 m. Robertson (1967), operating in the same geographical area as Langer et al. (1967), claims that vertical mixing of the AgI plume has been found at heights of 700 m above the terrain 7 km downstream of the generator site. However, in either the Langer et al. or Robertson studies, no mention was made of the instability as reflected by the temperature lapse rate. Smith and Heffernan (1954, 1956) report that while there was considerable variation from day to day, in general the silver iodide plume rose to heights of 1000-1500 m at a distance of 10 km from the generators, and thereafter rose very slowly if at all.

Limited measurements of the vertical diffusion of the silver iodide plume at Elk Mountain at distances of approximately 10 km downwind from the generator reveal that the tops of the plume are between 300 and 450 m above the terrain. On these occasions, the lapse rate was between 10.6 and 12.8 C km^{-1}, a highly superadiabatic lapse rate.

It is interesting to note that with our observed average Elk Mountain plume dimensions, namely, 2.0 km wide, 450 m deep and using a transport speed of 10 mps and generator output of 10^{15} AgI nuclei $gram^{-1}$, the calculated concentration of AgI nuclei within the core of the plume, assuming uniform dispersion, lies near 360 nuclei $liter^{-1}$. This corresponds quite well to the measurements of 100-200 nuclei $liter^{-1}$ (using NCAR counter) for a thirty minute nuclei travel time.

IV IMPLICATIONS

The results obtained by the University of Wyoming's Atmospheric Resources Research group have important implications concerning the treatment of orographic cloud systems. Foremost of these implications is the need for all operations to investigate the characteristics of the transporting winds, lapse rate (stability), etc., before conducting a seeding operation.

The horizontal dispersion angles of the plumes suggest that for

targeting within each treatment area the generator density must be determined to yield the desired nucleus concentrations within the clouds to be modified. Since under the most favorable conditions in the Elk Mountain area the vertical diffusion of the nucleating material did not routinely exceed 450 m in height, the treatment of a large vertical cross-section of cloud volume requires that the nucleating material be carried aloft via the updrafts within the cloud; and therefore, some definition of the updrafts associated with orographic clouds may be important.

In order to supply a constant source of freezing nuclei to a selected cloud volume, the dispensing generators should be located at distances no greater than 12 km from the cloud.

V. ACKNOWLEDGEMENTS

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TECHNIQUE FOR DETECTING ICE NUCLEI IN THE ATMOSPHERE

by

A. J. Alkezweeny

Meteorology Research, Inc.
Altadena, California 91001

The ice phase of clouds with tops above the freezing level plays an important role in the production of precipitation by the Bergeron-Wegener mechanism. However, the freezing of water droplets warmer than -40°C (homogeneous nucleation temperature) requires special types of particles called ice nuclei. Matured ice nuclei are only a small percentage of the total aerosol particles in the atmosphere. Their effective number is a function of temperature. However, in order to understand their effect on the cloud growth and precipitation development, a knowledge of their effective concentration at any temperature is required together with its variation in space and time.

At the present time, it is not very well understood why a certain particle acts as an ice nucleus at a particular temperature when others do not, and the only way to detect them is through their nucleation activity. Three types of nucleation are possible for ice nuclei to form ice crystals:

1. Contact nucleation. When nuclei come in contact with a supercooled water droplet (temperature below 0°C) causing them to freeze, this is called contact nucleation.

2. Sublimation. If the ice crystals form on the nuclei from the vapor phase without going through the liquid phase, the nuclei are referred to as sublimation nuclei.

3. Condensation and freezing. In this case, the nuclei act as condensation nuclei forming a water droplet and then freezing it. The nuclei may be called freezing nuclei. However, the term freezing nuclei is sometimes used for nuclei active in any of these processes.

The usual method of measuring ice nuclei concentrations is by cooling a known volume of air to a fixed temperature and counting the number of ice crystals which are formed in that volume. Three types of apparatus are available for counting the ice nuclei: the mixing chamber, the expansion chamber, and millipore filters.

The mixing chamber consists of a box which is cooled from the outside wall to a fixed temperature. Air is introduced into the box which is mixed with a supercooled fog. After a period of time, ice crystals

are formed which then can be counted. The supercooled fog can be introduced either by injection of moisture from a heated vessel containing distilled water connected to the box or by humidifying the air before mixing it.

In the expansion chamber, the air containing the nuclei is cooled by adiabatic expansion. In this manner, a cloud of supercooled fog droplets is formed. After this, the ice crystals may be counted. Expansion may be achieved by physically changing the chamber volume, pressurizing the chamber, and then relieving the pressure or by pumping the chambèr.

The ice nuclei which are formed in these chambers are detected either visually when they appear as a bright star in the light beam or when they are allowed to fall in a tray containing supercooled sugar solution where they grow large enough to be counted. Automatic ice nuclei detectors were developed in which the ice crystals were detected by acoustic sensors, as in the NCAR counter, or photoelectric detector, as in the MRI fast-response counter.

The major problem associated with these instruments is the formation of frost on the chamber walls. The splinters which might be released from the frost lead to an overestimate of the actual ice nuclei concentration. This problem may be overcome by covering the wall with glycerine or glycol. However, in time it becomes diluted and should be replaced. The liquid which is present on the walls absorbs moisture and hence reduces the supersaturation, especially in the mixing chamber.

It has been shown theoretically by Fletcher (1966) and experimentally in our laboratory and by others (Warner and Newnham, 1958; Alkezweeny, 1970) that the concentration of ice nuclei is not only dependent upon the temperature but also upon the supersaturation and its duration. Higher supersaturation and longer duration produce a higher nuclei count. Keeping this in mind, let us examine the characteristic of the expansion and mixing chambers. In the expansion chamber, in order to prevent moisture losses to the wall, rapid expansion is used. In such a case, the supersaturation and the required temperature are established only for a few seconds or less. This will result in underestimating the nuclei concentration. However, rapid cooling of the air may lead to instantaneous, high supersaturations which increase the concentration. The relative importance of these two effects is dependent upon the relative humidity of the air, the temperature, and the rate of expansion. In the mixing chamber, since it is cooled from the walls, the temperature in the center may be warmer than near the walls. Furthermore, high and uncontrolled supersaturations may also be produced during the cloud formation inside the box.

The technique for detection of the ice nuclei may be another source for error in the count. The visual count depends upon the experience of the observer. Also, there are some foreign particles which might look like ice crystals in the light beam. In the case of the supercooled sugar solution, if it is too cold or weak, ice crystals may be nucleated by their own contamination. Warm or too concentrated a solution may not detect the

nuclei. Furthermore, the solution should be left long enough to allow the ice crystals to fall onto it. If the time is too long, the growing crystals may join each other and cannot be differentiated. In the case of automatic counting, the ice crystal must attain a certain size if it is to be detected.

The millipore filter technique was first introduced by the Australians (Bigg et al., 1963) to measure ice nuclei concentration. In this method, a known volume of air is drawn through the filter and the nuclei can be detected and counted by cooling the filter to a fixed temperature in a supersaturated environment.

The earlier procedure of filter processing was by cooling the filter, humidifying it by placing a warm, wet pad a short distance above it for a minute or so and then pouring supercooled sugar solution on the filter surface. The ice crystals become visible and can be counted. It was found that the concentration of ice crystals is dependent upon the humidification time and the sampling volume. These difficulties may be caused by the high supersaturation and its duration which is inherent in this procedure.

An improved processing method was developed which removed many of these disadvantages (Stevenson, 1968). The exposed filter is impregnated with hot vaseline and then it is cooled from the bottom in a chamber where the temperature and supersaturation are controlled precisely. Since the filter is a poor heat conductor, the hot vaseline serves to fill the filter pores preventing the water vapor from condensing on the bottom side and improving the heat transfer through the filter. Continuing research on the filter technique at MRI has shown that the use of vaseline in this manner presents some problem (Alkezweeny, 1969, 1970). Due to the thinness of the filter, it is quite difficult to control its flow. If the vaseline creeps on the surface, it may cover existing nuclei and in some cases becomes a nucleation site itself. However, if a thin film of vaseline is placed underneath the filter, this problem is removed.

In the expansion of the mixing chamber, the nucleation could be sublimation, contact or condensation freezing. Moreover, a combination of these processes is possible, depending upon the nature of the nuclei, the temperature, the supersaturation and its duration. Unfortunately, these factors cannot be controlled. In the filter technique, these factors can be controlled precisely except that contact nucleation cannot be detected.

Fast response and accuracy for the nuclei count cannot be found in one instrument. For instance, the mixing or expansion chamber, especially with automatic counter, gives a reasonable time response, but the supersaturation is higher than in the real atmosphere. In the filter technique, the processing takes some time and the results will not be known immediately. However, it is simple and inexpensive. In the field, one needs only a sampling device and the filters can be sent to the laboratory to be processed. Little care is needed to maintain the sampler.

In summary, each technique has its advantage and disadvantage. Therefore, a detailed investigation into the different techniques and a comparison between them is badly needed.

ACKNOWLEDGEMENT:

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SIERRA CUMULUS

M. C. Williams and D. E. Lehrman

Fresno State College Foundation
Atmospheric Water Resources Research
Fresno, California

INTRODUCTION

The annual precipitation regime in the Sierra Nevada mountains of California is characterized by predmoninantly winter-time occurrences. Approximately 95 percent of the total annual precipitation occurs during the period October through April. Extensive agricultural development in the Central Valley of California has been based on the utilization of the water supplies represented by the accumulated high elevation precipitation. The occurrence of subnormal precipitation results in shortages in supply during the summer months when irrigation demands are at a maximum. During these periods, the degree of water resource development make it economically feasible to consider supplementing the natural supply through modification of the summer cloud systems despite their comparatively low runoff volume potential.

A project to investigate the potential for enhancing water supplies through seeding summer-time orographic cumuli over the high portions of the Sierra Nevada was developed in May 1966 (1). This project was designed in a step-wise manner to provide a tool for use by water resources groups within a period of three years. The four phases of the project consisted of: 1) hydrologic studies, 2) pair seeding, 3) quantitative determinations, and 4) forecast tools and physical models.

The project was conducted during the 1966, 1967 and 1968 summer seasons. Support for the project was provided primarily by the U.S. Department of the Interior, Bureau of Reclamation, Office of Atmospheric Water Resources, under Contract Nos. 14-06-D-5819 and 14-06-D-6592, with supplementary support from the Kings River Conservation District for field operations during the 1968 season. Research operations were conducted by the staff of the Atmospheric Water Resources Research, Fresno State College Foundation, with contract assistance for field operations from Atmospherics Incorporated, and hydrologic studies by Sierra Hydrotech.

HYDROLOGIC STUDIES

Resolution of the question of whether significant runoff could be expected in the watersheds of the high Sierra from summer cumuli represented a necessary first step. This phase which took the form of a hydrologic analysis of historical runoff records (2) was accomplished to 1) establish the potential for runoff, 2) provide basic analyses

for evaluation purposes, and 3) establish areas of highest potential for operations. Runoff was selected as the evaluation unit since 1) limited historical precipitation data is available in the study area, and 2) it represents the product of interest to user groups. Initial analyses of the data indicated that runoff from summer precipitation represented 2 percent and 3 percent of the total annual amount.

Runoff observations for a total of 29 stations were analyzed in detail for periods of 7 to 43 years using records for unimpaired streamflow. Maximum utilization of computer operations was employed due to the volume of data and analysis requirements. In this manner, it was possible to study a number of parameters which included: 1) volume of runoff on a unit basis chosen to be acre feet per square mile, 2) number of occurrences as defined to be a detectable increase on the annual hydrograph, 3) timing of runoff occurrence with respect to a significant event such as the end of winter snowmelt, and 4) the relationship of summer runoff to basin characteristics. The analysis technique consisted of separation of the systematic base and/or summer recession runoff from the total hydrograph. Actual separation was accomplished by use of a computer program developed for this purpose. The analysis period for each station was May 1 through October 31 for the available, historical record.

The results of the study covered a wide range of considerations pertinent to the problem. The first of these results indicated that the hydrograph characteristics for Sierra Nevada watersheds are such that summer precipitation occurrences could be distinguished. The volume of runoff from these summer occurrences was found to be highly variable, but was significant in amount as well as dependable in occurrence. Values ranged from 2 acre-feet per square mile to over 50 acre-feet per square mile, depending on basin location and particular year of occurrence. The number of runoff occurrences resulting from summer precipitation is not as variable as the volume. The analysis indicates that summer runoff occurs from a relatively small number of occurrences, averaging 7 to 8 per year.

Both runoff volume and number of occurrences suggest favored locations for summer storms. These locations represented high potential areas both from the standpoint of number of occurrences and runoff production. Identification of these areas resulted in the development of a map which portrays the potential for various areas in the Sierra Nevada (2).

Definite indications of the correlation between the physical characteristics of the watershed and runoff production were established by the analysis. In addition, the relationship between seasonal timing (time of occurrence with respect to a significant event) and runoff volumes was established. It was found that the particular event which was most applicable to this study was the end of snowmelt as defined by streamflow at key locations.

The study also resulted in an apparent correlation between potential

runoff production and precipitation types. The three types of precipitation occurrences that could be identified from runoff characteristics were: 1)isolated thunderstorms, 2) generalized thunderstorms, and 3) general storms. The two thunderstorm types were generally associated with southeasterly flow aloft while the general storms were of an organized nature similar to winter season systems with westerly flow aloft.

PAIR SEEDING

The second phase of the project consisted of activities to determine the potential for production of precipitation from previously non-precipitating cumuli through aircraft seeding (1), (3). This phase placed particular emphasis on the question of whether or not seeding would affect the relatively dry orographic cumuli over the high Sierra. In addition, these activities were designed to establish the factors responsible for effective seeding.

The physical features of the seeding area are characterized by the rugged mountains of the Sierra Nevada from Central California south to the Tehachapi Mountains. The mountains represent a major north-south barrier rising from the Central Valley to over 14,000 feet in some locations and descending abruptly to high pleateau on the eastern side. Seeding operations were restricted to the higher elevation portions of this area.

The meteorological systems associated with the three runoff producing occurrences fall into two general categories which can be characterized by their sources of moisture. Precipitation occurring from a source of moisture off the coast of California in the Pacific Ocean can generally be associated with organized systems resembling winter storms. These occurrences result in widespread precipitation which affects most of the area, and have been classified as general storms. A more common occurrence which has a source of moisture in the Gulf of Mexico results in the other two storm types. These are the isolated and general thunderstorms. The difference between these two types results from the timing and duration of southeasterly flow bearing moist air from the Gulf.

The experimental design basically consisted of seeding one of a pair of similar, non-precipitating clouds on a random basis, and observing both clouds before and after seeding. Selection of cloud pairs was accomplished on the basis of both visual observations and radar surveillance. Similar characteristics of growth, size, physical separation, lack of radar return and general appearance were used as criteria for selection.

Seeding was accomplished with aircraft units utilizing both dry ice and silver iodide for comparative purposes. Dry ice seeding was accomplished in the tops of the growing cumuli at various rates by means of a dispenser mounted in the aircraft cabin (3). Silver iodide was produced by pyrotechnic devices (3) attached to external racks on the aircraft, and released at the -5° C temperature level in the updraft portion of the cloud.

Observation of effects and meteorological parameters were made by a combination of equipment. Both visual and photographic observations were supplemented by radar measurements throughout the operational period which were documented by time-lapse photographs of the radar presentation. Rawinsonde measurements were made at three-hourly increments on operational days from a location at the Fresno Air Terminal. These rawinsondes were used to supplement Weather Bureau soundings made at synoptic times at more distant locations, and provide the basis for analysis of the physical properties of the storm systems. Time-lapse photographs were also used to document cloud conditions from a surface location near Fresno.

During the three project seasons, a total of 47 test cases (94 clouds) were developed. Analyses of various types were conducted to determine the significance of the effects observed. Basically, the observations used for these analyses may be summarized as follows:

Sample Size	47 Test Pairs	(94 Clouds)	
Precipitation Type	Reaching Ground	Virga	None
Seeded	21	13	10
Non-seeded	3	0	44

It should be noted that several test cases were eliminated from the evaluation because of inadequate observations of the effects.

Application of both Chi-square and McNema (4) statistical tests for significance to the above results indicate that seeding was responsible for producing precipitation from non-precipitating clouds with a significance level of .999 (null hypothesis rejected at the .001 level).

QUANTITATIVE DETERMINATIONS

Operations during the 1967 and 1968 summer seasons included activities specially designed to provide indications of the potential quantities of supplemental runoff to be achieved from orographic cumuli. These activities took the form of seeding to affect a particular watershed and evaluation of the amounts received. These activities were conducted on the basis of criteria developed during the previous phases of the study.

The particular target area used was selected on the basis of the availability of unimpaired, historical streamflow records and the physical characteristics of the watershed. The criteria for selection included the representativeness of the area, runoff potential, amount of vegetative cover and predictability of runoff. The target watershed selected was the Bear Creek basin above Lake Thomas A. Edison on the San Joaquin River. This watershed has an area of 53.5 square miles, and is located adjacent to the crest of the Sierra Nevada. Four control watersheds were used to predict the effect of unseeded storm activity on the target area. These watersheds were located both north and south, but not adjacent to the target area, and were selected for their

similarity in runoff and historical characteristics to the target watershed (Figure 1.).

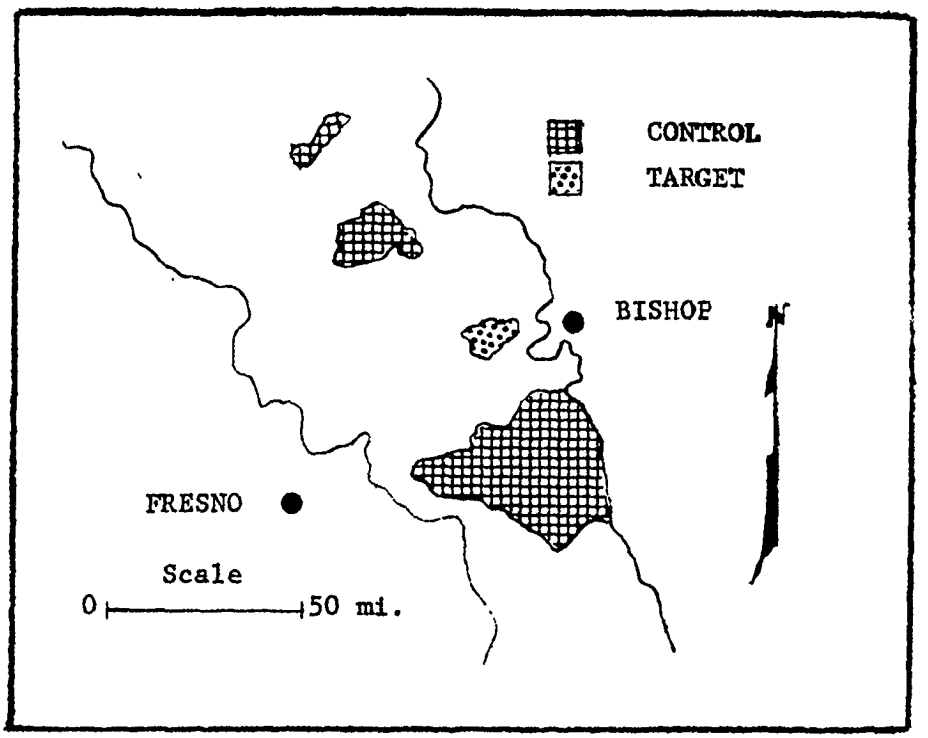

Figure 1. Location Map

Operations were restricted to the period after the end of snowmelt in order to avoid the effect of melting snow on runoff computations. In this manner, runoff occurrences could be attributed to summer precipitation with confidence. The end of snowmelt was defined to be the period after the mean daily flow of the Kings River above North Fork fell below 1350 cfs. The total summer period normally occurred between mid-July and October 1.

A total of seven area test case occurrences which in some instances involved multiple days were selected for analysis. This represented three test cases in 1967 and four in 1968. Selection of test cases was based on adequacy of observations, operational capabilities and seeding opportunities. Seeding was conducted with silver iodide pyrotechnics dispensed from aircraft in suitable clouds immediately upwind of the target watershed on as many opportunities as possible.

The evaluation design was develped prior to 1967 operations during

the winter of 1966-1967. Based on the historical runoff record for the 13-year period 1952-1964, a regression equation was developed for the target and control areas to permit prediction of amounts over the target area. This relationship was essentially a linear regression which took the form $R = K_1R_1 + K_2R_2 + K_3R_3 + K_4R_4 + K_5$ where R represents the runoff in each watershed. This regression equation was tested for sensitivity to incremental changes in runoff in order to develop an estimate of the number of occurrences required to give specific increases for the target area at significance levels of .90, .95 and .99. This estimate indicated that on the basis of an average of 7.2 storms per season, two seasons would be required to verify increases of 50 percent to 100 percent with a significance of .99. This estimate was used as the basis of the project design.

The unit of runoff used in the evaluation was acre-feet per square mile. This unit provided comparability between basins of various sizes. Runoff records were investigated in detail and tested to insure the accuracy and reliability.

The results achieved by seeding of the seven test cases were analyzed on the basis of both individual years and the combined period of operations. Application of the regression analysis to the basic streamflow data provided the results given in Table I.

TABLE I

YEAR	TEST CASES	SEEDED DAYS	Pred. R/O a.f./sq.mi.	Act. R/O a.f./sq.mi.	Difference a.f./sq.mi.
1967	3	3	18.23	24.48	6.25
1968	4	9	8.25	31.19	22.65
1967-1968	7	12	25.77	55.67	28.90

Application of Students' T test to these data provides the results given in Table II.

TABLE II

YEAR	INCREMENT	Apparent % Increases	t
1967	6.25	34	$<$ .90
1968	22.65	266	$\approx$ .995
1967-1968	28.90	104	$\gtrapprox$ .995

$$\text{Where } t = \frac{(RActual - RPredicted)/n}{\sigma/\sqrt{n}}$$

$$\sigma = \sqrt{5.89}$$

The actual amount of increase in runoff from the entire basin associated with these efforts during the 1968 season was approximately 1200 acre-feet. Manual analysis of the hydrographs for the historical record

revealed no comparable occurrences during the 13 year period.

The results of the evaluation may be summarized by the following points:

1) The evaluation of project activities indicates that increases in runoff of the order of 100 percent of 250 percent can be achieved by seeding summer-time orographic cumuli.

2) The most productive storms are those which have occurrences on two or more successive days.

3) The number of favorable weather occurrences including those prior to the end of snowmelt can be expected to be significantly larger than those experienced during the post-snowmelt period.

4) The potential area over which cloud conditions from which increases of the type indicated here can be achieved represents a significant portion (approximately 15 percent) of the total Sierra Nevada area, and is much larger than the 53.5 square mile target area used for this study.

FORECAST TOOLS AND PHYSICAL MODELS

Analyses were conducted for the twofold purpose of increasing understanding of the physical process involved in summer cumuli development and developing tools to forecast the occurrence of suitable seeding conditions. A number of correlations were attempted between various parameters and seeding effectiveness (1). The parameters involved included: 1) cloud depth, 2) cloud top temperature, 3) cloud base temperature, 4) precipitable water, 5) 500 mb and 700 mb wind direction, 6) seeding materials and rates, and 7) seeding level and temperature. These correlations provided the following information regarding the activities:

1) A minimum cloud depth of 5,000 feet was required for seeding to be effective.

2) Cloud depths which exceeded 12,000 feet normally produced precipitation naturally.

3) Available moisture was highly variable in the test cumuli and natural precipitation can be expected from only the more "moist" clouds. Seeding produced precipitation reaching the ground with only nominal preciptable water quantities in the cases where the minimum cloud depth requirement was met.

Analysis of standard meteorological parameters was accomplished for both horizontal pressure surfaces and vertical cross-sections. Horizontal analyses included streamline portrayals which assisted in identification of convergence zones on operational days (1). Primary emphasis

was placed on vertical cross-sections prepared for as many intervals as possible. Basic data for these analyses were derived from a combination of standard Weather Bureau stations located at Oakland, Vandenberg, Yucca Flat, Yuma and Winnemucca. Whenever possible, these observations were supplemented with data from the project soundings made in Fresno.

The variables analyzed for the cross-sections were potential temperature, equivalent potential temperature, mixing ratio, temperature and relative humidity. These analyses assisted in the identification of moisture sources, moisture levels, stability and temperature regimes required for high potential seeding days.

Figure 2 provides an example of a typical seeding situation over the high Sierra.

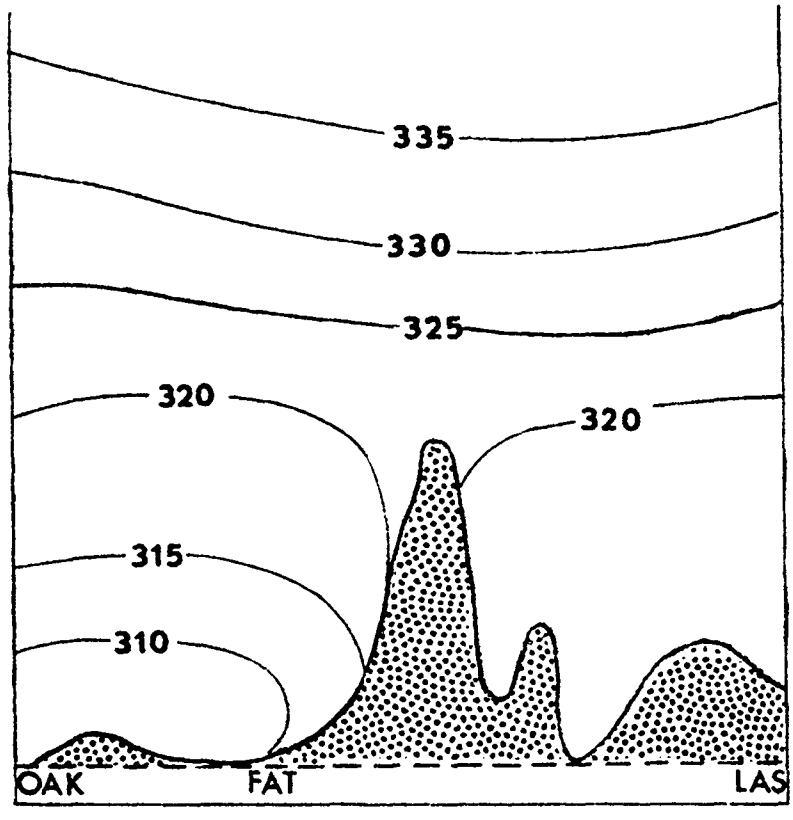

Figure 2. Vertical Cross-Section Showing Isopleths of Potential Temperature from Oakland, California to Yucca Flat, Nevada.

The second major aspect of this anlysis portion of the project was the development of a forecast tool which would aid in determining those periods and conditions of high potential for increasing useable water supplies (5). The primary criteria applied to the overall project required that the techniques and operations developed must be of such nature that anyone with reasonable meteorological knowledge could apply

them effectively through the use of standard, commonly available data. In other words, the forecast tool developed would be based on routinely available Weather Bureau data as opposed to data which might require specialized equipment.

The study was designed to develop a statistical model with which to predict the occurrence of general convective storms during summer periods. The model was designed to serve as one input to the decision-making process for project operations rather than the sole criteria for seeding operations. The data used to develop the model consisted of the 0400 PST rawinsonde from Oakland, San Diego, Yucca Flat and Yuma.

The particular statistical tool used was a standard discriminant analysis for two groups (4). The groups selected were: 1) days with general convective activity, and 2) days with isolated or no activity. This analysis tested each of the variables selected and resulted in a relationship which provides the probability for suitable conditions based on an index computed from the measurements from routine ESSA Weather Bureau rawinsondes. The resultant discriminant function derived by the analysis was statistically significant at the .999 level by the F-ratio test. This relationship has been put in the form of a probability curve (Figure 3) which can be readily used by anyone with access to a Class A Weather Bureau station.

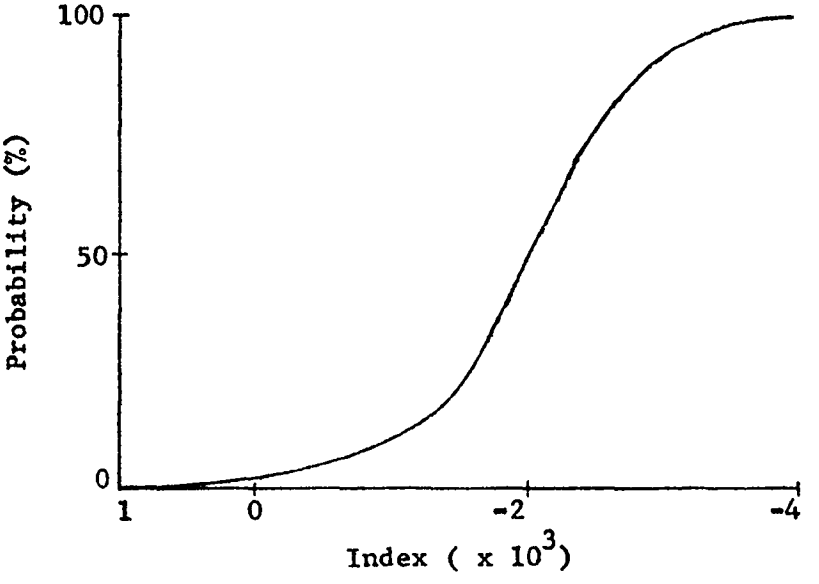

Figure 3. Probability vs. Computed Index Curve. Sierra Cumulus

Following development of the model, evaluation of its effectiveness was conducted using data from the summer of 1969. On the basis of observations from mountain and valley stations, each day was categorized into one of the two previously stated groups of weather. These categorizations were then compared with the corresponding probability forecasts. This comparison showed that discrimination between the two groups is apparent and generally demonstrated the effectiveness of the tool.

The model developed is applicable to various other activities as well as weather modification projects. It can serve as a valuable aid to both water runoff forecasts and local area forecasts. Such local area forecasts are issued routinely by the Weather Bureau for the public and for the National Park and Forest Service personnel concerned with fire-weather information.

CONCLUSIONS

The general goals of the project were achieved in the three-year design period. The statistical significance of the evaluation of quantities of additional water produced by seeding summer, orographic cumuli were adequate to permit design of operational projects as evidenced by the fact that one local water-user group has initiated such a project for the summer seasons of 1970 through 1972. The high degree of statistical significance for the evaluation can be attributed to the fact that increases achieved were considerably higher than the design values used. Some questions remain regarding the physical processes and the parameters responsible for successful seeding. However, the results appear to be adequate for operational purposes in the sense that the necessary guidlines for decision-making have been attained.

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THE THEORY AND PRACTICE OF HAIL SUPPRESSION

A. S. Dennis
Institute of Atmospheric Science
South Dakota School of Mines and Technology
Rapid City, South Dakota

1. INTRODUCTION

Cloud seeding programs designed to suppress hail for economic benefit have existed in the United States intermittently since 1948. The theory of hail suppression has lagged behind its practice and there is still a lack of agreement among cloud physicists concerning the effectiveness of such hail suppression projects.

One reason for the lack of agreement on the effects of cloud seeding upon hailstorms is the wide range of possible effects. Some of these are shown in Table 1.

TABLE 1

Possible Ways to Affect Hailstorms by Seeding

Class of Effect	Effect
1. Cloud microphysics	a. Glaciate cloud b. Introduce competing embryos
2. Cumulus dynamics	a. Intensify the updraft b. Shorten or lengthen lifetime of cell c. Strengthen competing cells or competing mesosystems
3. Radiation	a. Produce artificial cirrus shield

It is seen that the effects encompass atmospheric processses on all scales from cloud microphysics to the synoptic scale. Furthermore, one cannot decree that one or more of the processes will operate and the others will not. An experimenter may determine to glaciate the tops of all towering cumulus clouds in an area. In doing so, he cannot avoid the creation of an artificial cirrus shield spreading perhaps 50 to 100 miles downwind of the seeding area.

Because of the complexity of the effects produced, some research workers have turned to numerical models for assistance. Most numerical

models of convective storms require large amounts of input data and high speed computers to obtain solutions in reasonable amounts of time. These factors have led some workers to visualize for the future the "2001" hail suppression technique. The "2001" hail suppression technique is designed around a very large computer (HAL) capable of handling in real time a torrent of data from instrumented aircraft, radars, lidars, and other sensors (Fig. 1). After due consideration (accomplished in a matter of milliseconds), HAL issues detailed seeding instructions tailored to the particular hailstorm under consideration. The instructions are detailed and specify the type and quanity of seeding agent and the time and place for its introduction.

The realization of even a reasonable facsimile of the "2001" hail suppression kit would cost millions of dollars. Under this approach, there is little hope of hail suppression becoming a reality in the United States until after the government has allocated 5 to 10 million dollars to hail suppression research annually over several years. Present trends in the federal budget do not permit optimism concerning this possibility.

2. REQUIREMENTS OF AN OPERATIONAL SYSTEM

If it is agreed that the objective of research into hail suppression is hail suppression, and not merely increased understanding of hail formation processes, it is appropriate to examine the ultimate operational system as a guide in the design of hail suppression experiments. We identify three requirements for operational hail suppression systems:

1. The operational system must be unsophisticated (i. e., cheap) enough to ensure a favorable benefit/cost ratio.

2. The hail suppression effect must be substantial, on the order of 50 to 100% reduction in damage.

3. The system must produce no significant harmful side effects such as adverse changes in rainfall or the level of air pollution.

The demand for a relatively cheap system arises from the fact that hail damage is not a large factor in the overall economy of this country. Hail damage in the United States amounts to some $300,000,000 a year; this figure can be put in perspective by noting that automobiles cause this much damage every month. Furthermore, hail damage is widely distributed, so that a single operational project can work upon only a small part of the national hail picture. A region which might be covered by a single hail suppression project, such as a grouping of five or ten counties in a northern Great Plains state, may suffer on the average $1,000,000 in hail damage per year. This sets an upper limit on the complexity of the system which can be mounted to suppress the damage.

The requirement that suppression effects be substantial relates in part to the requirement for a favorable benefit/cost ratio and also to the likelihood that public support for a hail suppression program cannot be maintained unless there is a fairly obvious reduction in hail damage. A hail suppression program producing only a 5% reduction in hail could be a paying proposition if done cheaply enough. However, such a program would not enjoy popular support for long because, to the casual observer, there would be no evidence that it was producing an effect. The requirement that suppression effects be substantial has one beneficial side effect; it eases the task of the statisticians assigned to the evaluation of the experiment!

The most likely harmful side effect of a hail suppression program would be a change in rainfall distributions. Even a 5 or 10% reduction in rainfall in a dry farming area could offset any benefits obtained by suppression of hail. Therefore, hail suppression experiments must be evaluated carefully to see if seeding is affecting rainfall as well as hail. Mere suspicions of rain suppression effects associated with the Blue Ridge Hail Suppression Project led to its being terminated by legislative action.

3. THEORETICAL BASIS FOR HAIL SUPPRESSION

Some recent findings in hail research suggest that the "2001" hail suppression technique may not be required. Numerical modeling studies under the most restrictive assumptions have shown that hailstones are a logical product from most thunderstorms of the northern Great Plains region with maximum updraft speeds in excess of 15 m sec^{-1}. No special requirements concerning superadiabatic liquid water content, peculiarities in the shape of the updraft profile, spongy hailstone growth (permitting the wet hailstone growth rate to be exceeded), or the recycling of hail embryos are required to explain the falls of 1/2 to 1-inch hailstones commonly observed in Great Plains thunderstorms. Twenty to 50-μ particles in the lower part of a developing convective cloud need only a single ascent to the -15C to -30C region and the ensuing fall to grow sufficiently by accretion to reach the ground as hailstones (Fig. 2). Thus giant salt nuclei, entrained ice crystals, and dust particles all appear as possible hail embryos. It makes no particular difference whether or not the stone's trajectory carried it above the peak in the updraft profile, although the stones can grow larger when they spend some time just above the peak in the profile. Solid embryos falling into the upper part of a hail cell can also reach the ground as hail.

The ease with which hail forms in the numerical models matches the observation that hail is very common in Great Plains thunderstorms, especially aloft. The lack of large hailstones in the numerical models' output suggest that large hail is the result of special circumstances, such as recycling. It is fortunate that only one hailstone in a thousand or so encounters these favorable circumstances.

The reference to hail as a logical precipitation form in Great Plains thunderstorms does not rule out the formation of rain by the same storms. The rain that reaches the ground from Great Plains' thunderstorms has two sources. One is the particles which grow sufficiently by accretion to exceed the local updraft speed and fall out before rising high enough in the cloud to be frozen ("warm rain"). The other is the graupel or hailstones which are small enough to melt completely before reaching the ground. Such particles may fall from clouds whose updrafts never exceed 15 m sec^{-1} and thus never produce significant hail, from the outer parts of clouds whose cores are active hail producers, or from the upper part of a hail-producing cloud after the updraft has weakened.

Continued theoretical research on such specific problems as accumulation zones, supplemented by some field observations, should increase further our understanding of hail formation processes. However, experiments in hail suppression could accompany continued basic research.

The glaciation of the upper portions of cumulonimbus clouds to slow the growth of hailstones is still the most straightforward and promising approach to hail suppression. There is evidence that cumulonimbus clouds can be glaciated down to about the -10C level by seeding with acetone-silver iodide generators on aircraft flying below cloud base or making penetration runs. Rockets, artillery shells, and free-falling pyrotechnics are also acceptable delivery systems from the meteorological point of view, although they may be ruled out by cost or safety considerations.

The introduction of additional hail embryos to reduce hailstone sizes is an intriguing idea, but it is unlikely that this could be accomplished directly by silver iodide seeding unless the cloud base temperature were very low (say -5C). The ice crystals thus produced would not achieve sizes sufficient to permit accretional growth until they reached about the -12C level, by which time hailstone embryos from the lower part of most convective clouds would already have achieved diameters of several hundred microns. Turbulent mixing might permit the ice particles produced by seeding to act as hail embryos within neighboring updrafts a few minutes later. Seeding below the base of the cloud with finely ground salt appears a more promising way to increase the number of hail embryos within the unmixed updraft core, and might also precipitate some of the cloud water as "warm rain". A field test of the method would be interesting.

4. CHOICE OF EXPERIMENTAL DESIGN

Numerical modeling of hailstorms has not yet reached the point where seeding techniques can be adopted for operational hail suppression without testing on a randomized field experiment. Regardless of the seeding technique selected for testing, one must choose an experimental design. Two designs will now be considered.

The Hail-Case Design. This experimental design involves the selection of particular storms as "hail cases." Once a hail case is selected, a random decision is made to seed or not seed it. In either case the hail produced by the storm is monitored and a comparison of the seed and no-seed cases is made to detect possible seeding effects.

The only randomized hail-case experiment conducted so far in this country is that of Colorado State University from 1964 to 1967. This experiment involved seeding from below cloud base by an aircraft equipped with acetone generators. Unfortunately, the experiment produced an inconclusive result. It could be that this was due merely to the use of an insufficient quantity of silver iodide. However, the delay in the start of seeding which is intrinsic to the hail-case approach may render it futile.

In order to avoid seeding storms which would not persist for some tens of minutes, the declaration of hail cases in the Colorado experiments was delayed until the storms fulfilled certain criteria, including strong radar echoes from 30,000 ft. In brief, the storms were practically full grown hailers before seeding was undertaken. It may be, however, that the crucial requirement in hail suppression by micro-physical processes is to produce additional hail embryos early in the life of a convective cell. Turning to dynamic effects, the introduction of silver iodide into the updrafts of an already dynamic vigorous thunderstorm may stimulate it through the release of latent heat. Observations in South Dakota have shown that the likelihood of heavy precipitation from a convective cloud is increased if there is a positive correlation between the field of updraft speed and temperature excess with the cloud; this correlation would be increased by the glaciation of the supercooled water in the updrafts.

The Area Experiment. An alternative to a hail-case experiment is an area experiment, in which randomization is applied by declaring certain days "no-seed" days. On "seed" days all convective clouds approaching or developing within a predesignated target area are subjected to a seeding treatment, much as they would be on an operational program. From personal experience the author suggests an area of 3000 to 5000 square miles to be seeded by two or three aircraft, which are directed from a radar-equipped field office, and equipped with 200 to 300 raingages and hail indicators. Such experiments do not require extremely elaborate instrumentation and can be mounted at a cost of approximately $250,000 per project season.

The area experiment offers a number of simplifications as compared to the hail case design. Analysis of an area experiment can be carried out without detailed studies of individual hailswaths. The problem of deciding whether or not a particular hail streak at the ground should be assigned to the "hail case" is thereby avoided. As hailswaths are often intermittent or branched, this can be a difficult decision.

In an area experiment many cells can be treated during a single operation, providing large statistical samples over a few seasons containing convective cells of different sizes and intensities. Furthermore, the seeding treatment can be applied early in the lifetime of each convective cell if this is considered desirable.

The area experiment will also lead to releases of latent heat in the updrafts of some large hail-bearing clouds, but this is compensated to some extent by releases of latent heat in other cumulus towers in the vicinity. Even if a few cells are stimulated and produce additional hail, there may result a compensating suppression effect in an area of several hundred square miles related to increased atmospheric stability by subsidence. This second-order effect would likely be overlooked in a hail-case experiment.

5. SUMMARY

Assuming that present support levels can be maintained, meaningful research into hail suppression can be carried on at a number of locations within the United States during the next several summers. To make research into hail suppression contingent upon the acquisition of very sophisticated hardware, and thus upon extensive new sources of research funds, would be a mistake. The relatively modest research programs of the past few seasons have provided good insights into hail formation processes and have shown that they are rather straightforward in many cases. Theoretical investigations using simple numerical models can be conducted at reasonable cost and should be continued, along with supporting field observations.

The author suggests randomized cloud seeding experiments involving predesignated target areas in addition to the proposed "hail case" experiments. All experiments of either design should pay equal attention to rainfall and hailfall distributions.

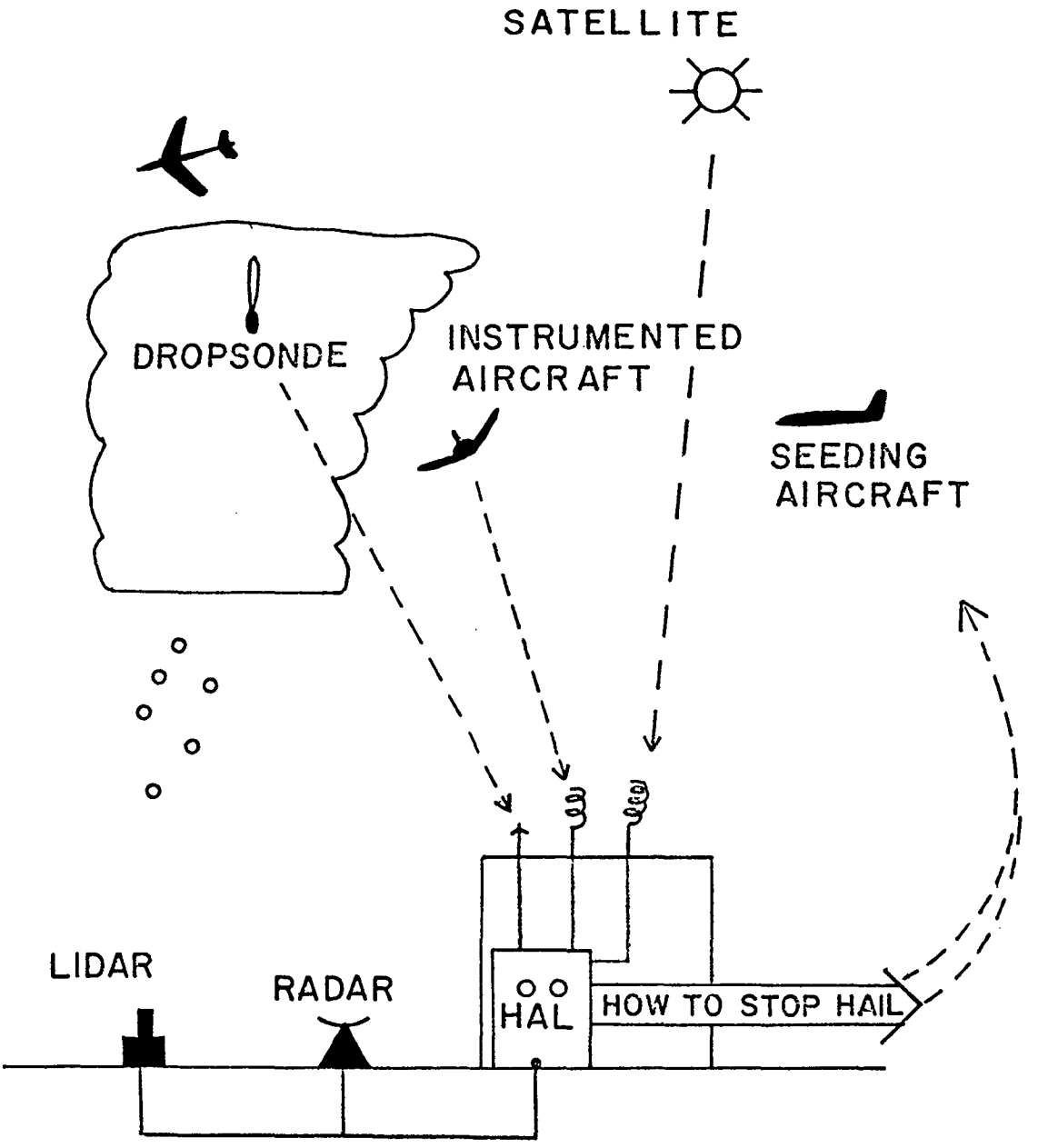


Fig. 1. The "2001" hail suppression technique.

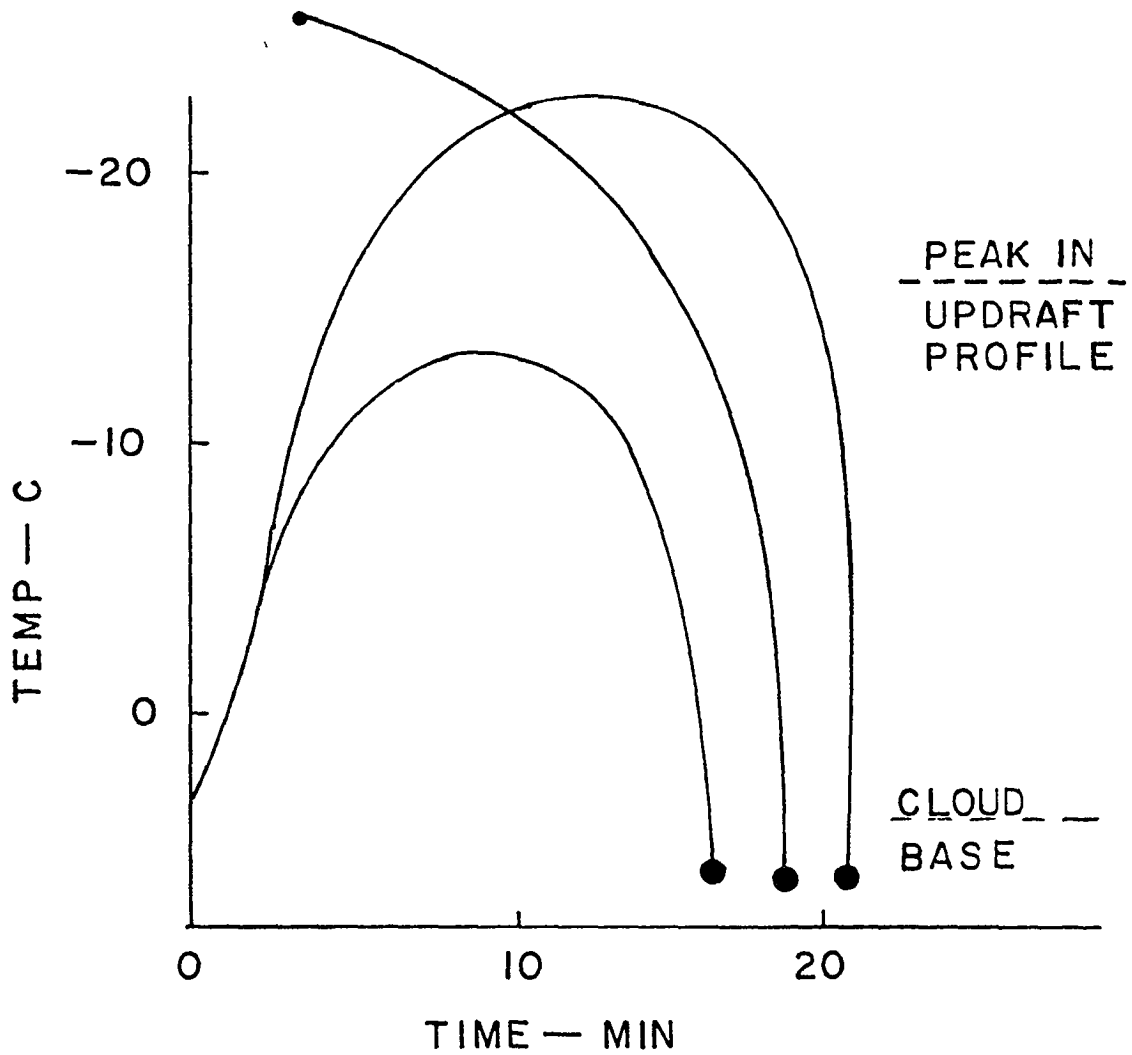


Fig. 2. Various possible trajectories for growing hailstones.

NUCLEATION EFFICIENCIES OF AgI-NH_4I AND AgI-NaI ACETONE SOLUTIONS AND PYROTECHNIC GENERATORS AS A FUNCTION OF LWC AND GENERATOR FLAME TEMPERATURE, A PRELIMINARY REPORT

By: John A. Donnan, Donald N. Blair,
William G. Finnegan, and Pierre St.-Amand

Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
Rapid City, South Dakota 57701

U. S. Naval Weapons Center
China Lake, California 93555

ABSTRACT

The activity of ice nuclei depends upon their chemical composition, physical properties, and their environmental history. Glacogenic nuclei, generated in clouds at ambient temperatures below their maximum effective temperature, function well but those involving complexes of silver iodide and alkali iodides are considerably altered by residence in warmer moist air or in cloud. In order to find an acetone burner system that would result in relatively pure AgI so that the effects of exposure of the nuclei to the environment would be minimized, Vonnegut's earlier concept of using NH_4I as a solubilizing agent in an acetone solution was tested in the South Dakota School of Mines' nucleation test facility using a Lohse burner. Nuclei produced by the NH_4I-AgI systems are effective at higher temperatures than those of the NaI-AgI system. Values in excess of 10^{11} snowflakes per gram of AgI have been attained at -4°C with a 25% solution of NH_4I-AgI. The NaI-AgI system produced fewer nuclei than the NH_4I system at all temperatures above -8°C.

Numerical output of effective nuclei of the NaI-AgI system appears relatively unaffected by changes in burner flame temperature. Numerical output of the NH_4I-AgI system is markedly improved by reduction of the flame temperature. Optimum results are expected at flame temperatures of about 700°C.

The effectiveness of the nucleants, from pyrotechnics and from acetone systems, as a function of the liquid water content of the cold boxes depends upon the chemistry of the nucleant, and upon the temperature. These numerical counts of snowflake/gram from nucleants having little or no complexing agents or soluble components appear to be higher at higher temperatures and less dependent upon the liquid water content.

For seeding clouds from below cloud base or under conditions in which the nuclei have to pass through warm moist air or cloud, it seems

clear that those having only slight amounts of solubilizing agents, such as the LW 83 pyrotechnic or the NH_4I-AgI acetone system, are markedly superior.

INTRODUCTION

In 1949, Vonnegut devised a process of producing silver iodide ice nuclei by combustion of acetone solutions of silver iodide and ammonium iodide. The ammonium iodide functions as a solubilizing agent for the silver iodide and is destroyed in the flame, leaving the silver iodide as the only solid product of combustion.

In 1950, Vonnegut, while improving the technique of preparation of the acetone solution of silver iodide, substituted sodium iodide for the ammonium iodide. Sodium iodide is not destroyed by pyrolysis or combustion, and is not separated from the silver iodide during the generation process. Nuclei generated using the silver iodide-sodium iodide-acetone system are therefore mixtures of these iodides; their ratio dependent on the original mixing ratio (nominally 2AgI-NaI) and their physical properties now a function of the specific composition rather than those of pure silver iodide.

It has become abundantly clear that the activity of complex nuclei such as 2AgI-NaI varies with the length of their exposure to the atmosphere, at varying relative humidities and temperatures. A generator may yield nuclei showing high activity at $-5^{o}C$ when generated in cloud at $-5^{o}C$; but no activity until the $-14^{o}C$ level when generated out of cloud at temperatures above $0^{o}C$.

It occurred to two of the authors (Finnegan and St.-Amand) on evaluation of this evidence, that a marked improvement in ice nuclei generator technology could be achieved by a simple return to the silver iodide-ammonium iodide-acetone system.

TECHNIQUE AND APPARATUS

A Wind Tunnel/Cloud Chamber Facility developed by the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology has been operational since January 1970. Since that time, activity tests have been conducted on several different pyrotechnic cloud seeding generators as well as several standard acetone generators. The results obtained have been in general agreement with normally accepted values.

The facility consists of a wind tunnel in which cloud seeding generators can be operated and in which the air speeds can approximate those encountered in flight. The effluent from the generator is diluted and then delivered simultaneously to each of five, identical cold boxes each of which can be stabilized to any desired temperature between $0^{o}C$ and $-20^{o}C$. The liquid water content (LWC) of the fog in each box may be varied from 1 gm/m^3 to 8 gm/m^3.

A compartive study of acetone solutions of AgI-NaI and AgI-NH_4I is presently underway at the Institute. This paper is a report on some of the preliminary data of importance to the meteorological community. Comparable pyrotechnic data are also shown.

FORMULATIONS

Solutions were prepared in 2 to 1 molar ratio of AgI to NaI and to NH_4I, according to the following formulations:

TABLE 1. Stock Solutions

$NH_4I \cdot 2AgI$	$NaI \cdot 2AgI$
25.0% AgI	25.0% AgI
7.7% NH_4I	8.0% NaI
3.0% H_2O	3.0% H_2O
64.3% Acetone	64.0% Acetone

RESULTS

Figure 1 shows standard numerical activity data for 5.5% solutions of these materials. These data were collected at a LWC of 5 to 6 gm/m^3. There appears to be little difference in performance between the two materials from -10^0C and colder, but at about -7^0C the slope of the curve for the AgI-NaI nucleant approaches the vertical, but the slope of the curve for the AgI from the AgI-NH_4I system is about 30 crystals/gram/deg c, even at -6^0C.

A series of tests were conducted in which all five cold boxes were maintained with fog at the same temperature ($\pm.5^0$), but the LWC was varied from 1 gm/m^3, in the driest box, to 8 gm/m^3, in the wettest box. From test to test the box temperatures were allowed to vary over a range of 5 or 6^0C but for any given test all mean box temperatures were within 0.5^0C of each other.

During these test the flame temperature of the acetone generator was monitored with a bimetallic pyrometer. The number of effective nuclei obtained from the AgI-NH_4I solution was found to be dependent upon the flame temperature. No comparable temperature dependence was observed with the AgI-NaI solution.

Figure 2 shows data from the tests on AgI-NaI solution. Each curve represents a test run at a different cold box temperature--but at the same flame temperature. At -4.5^0C active nuclei were undetectable except in the wettest box, while at -5.5^0C crystals were observed with LWC values of 6 to 8 gm/m^3 and at -6.5^0C some active nuclei were observed at all liquid water concentrations.

It is probable that the aerosols from NaI bearing solutions function by contact nucleation in the wettest boxes. The wettest boxes have a greater number of water droplets per unit volume, hence a greater chance for contact with a particle of the nucleating material. This mechanism may be responsible for some of the positive seeding results when nuclei from the AgI-NaI solution were generated in adequately cold clouds in field experimentation.

Figure 3 shows the comparable data for nuclei from the AgI-NH_4I solution. All these tests were conducted at about -6°C; the variation is probably due to the difference in flame temperature of the acetone generator--the effectiveness increased as the flame temperature decreased from 1040°C to 730°C.

Solutions used in these tests were 14.7% AgI. Similar tests were attempted with 5.5% solution but present sampling limitations made it impossible to inject sufficiently large samples into the cold boxes at -6°C, and warmer, to obtain reliable results. At -7°C and colder good results can be obtained with 5.5% solution.

It appeared likely that such high efficiencies at warm temperatures would result in a drastic reduction in effective nuclei at colder temperatures. This hypothesis was tested by making several standard test runs from about -5°C to -20°C, while LWC was held constant in all boxes at 5 - 6 gm/m^3. These data are shown in Figure 4, and show efficiencies of about 10^{14} at -17°C which suggest that the total number of particles generated are not seriously decreased. Indeed, the comparison of efficiency curve from the effluent of the 5.5% solution of AgI-NH_4I (shown in Fig. 1) with the curve of the 14.7% solution shows a close similarity, as does the curve for the 25% solution.

These data appear to show that efficiencies at warm temperatures may be more strongly influenced by the nature or morphology of the nuclei than nuclei size.

Figure 5 shows data obtained from three different pyrotechnic seeding generators, designated EW-20, LW-83, and ARC SI-150 (see paper II of this series; ARC formulation is not available). The smoke from the EW-20 flare exhibits a temperature effectivity spectrum similar to products of the AgI-NaI solution while smoke from the ARC and LW-83 flares exhibit characteristics similar to the products of the AgI-NH_4I solution. The combustion products of the EW-20 flare produces a mixture of K_2O and KI with AgI while the others do not produce products showing similar hygroscopic characteristics.

CONCLUSIONS

1. On the basis of data presented we believe that ice nuclei which are hygroscopic complexes of AgI with sodium iodide are not effective as ice nuclei if exposed to a moist environment at temperatures warmer than -5 ± 1C.

2. It is evident that an acetone solution of AgI-NH_4I (the optimum concentration to be determined and which may be important) produes nuclei that

(a) are highly active at all LWC concentrations at -3.5°C, and

(b) there is no reason to expect that they would be destroyed as active nuclei upon exposure to warm, moist environments, except by solution of the smallest particles in large droplets.

3. It is obvious that cooler flame temperatures produce higher nuclei counts at warm cloud temperatures, while still producing good nuclei counts at colder temperatures.

4. We believe that, because the nuclei generated from the AgI-NH_4I solution are not destroyed as active nuclei in warm, moist air, injection of this material at cloud base (even if warmer than 0°C) would provide an abundance of nuclei from -4°C to the -20°C level. This should be possible because of the size-temperature dependency for nucleation. The abundance of particles too small to be active at -6°C would, as they are carried aloft, become active at the colder temperatures until they are all nucleated. This would not be the case with the nuclei from the AgI-NaI solution because these nuclei, large and small alike are susceptible to solution in their water droplets, by whatever mechanism one wishes to consider, thus these dissolved nuclei cannot affect freezing until the droplet is in the temperature region which would permit the AgI to precipitate out of solution (on the basis of solubility constants) or until the droplet reaches the temperature region in which spontaneous nucleation would occur.

5. We believe considerable reappraisal of all seeding materials are in order. The fact that some flares have poor warm temperature characteristics, while others do not, would imply that users should develop a greater understanding of these materials and there should be a more conscientious effort to "tailor" seeding projects to the materials being used or conversely.

6. Finally, users of seeding materials must be more precise when reporting results. A complete description of the seeding materials is in order.

ACKNOWLEDGEMENTS:

We wish to acknowledge the contributions of Miss Dianne Dorland who contributed much of the information on LWC. We also wish to thank Mr. Charles Tollinger whose patience, advice, and interest has contributed greatly to making this facility a working reality. The following agencies supported the research: The U.S. Department of the Interior, Bureau of Reclamation under Contract No. 14-06-D-6796; the Department of Naval Research under Themis Contract No. N00014-68-A-0160, and the Naval Weapons center, China Lake, California under Contracts No. N60530-67-C-1289 and N60530-68-C0006.

FIGURE 1

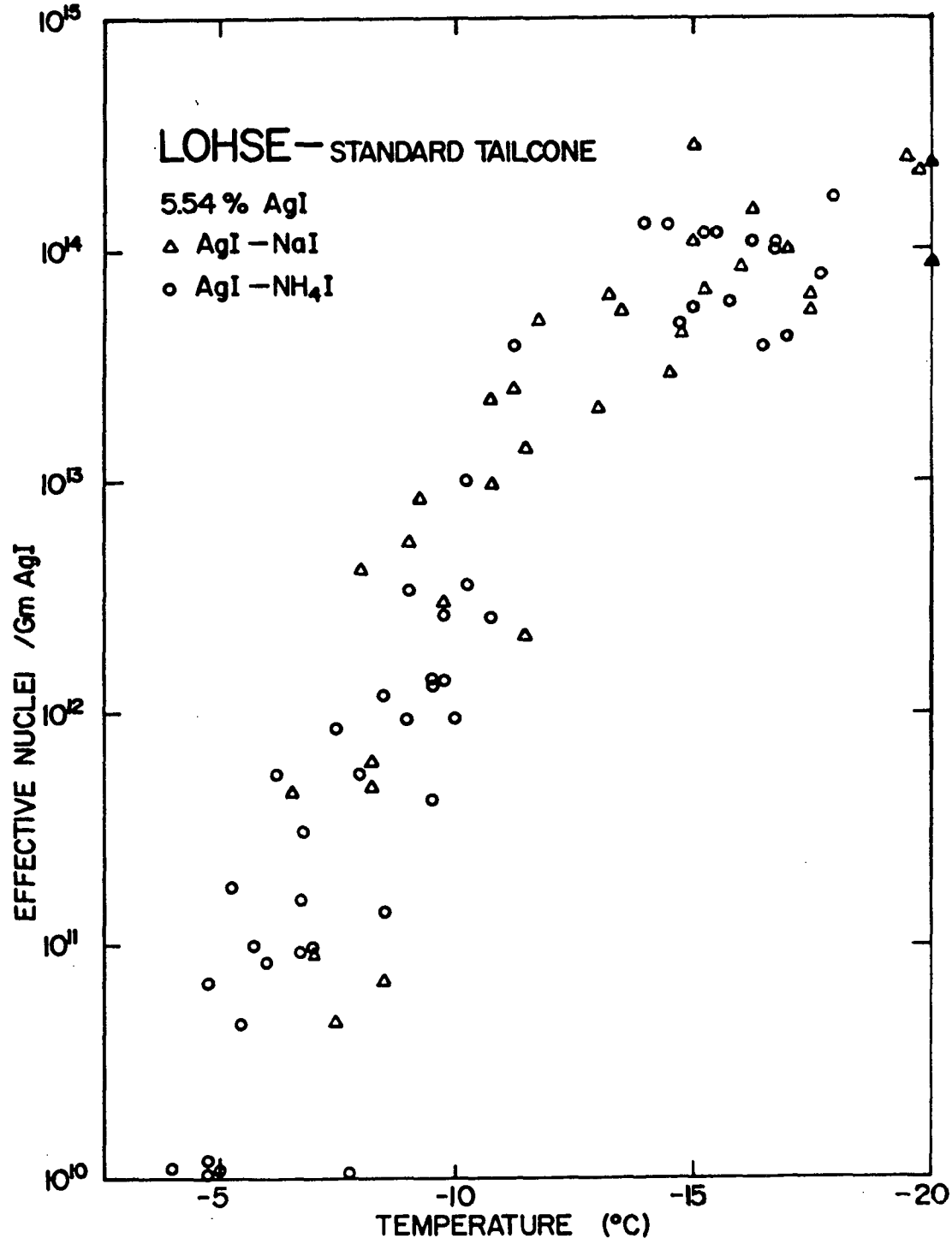

LOHSE – STANDARD TAILCONE
5.54 % AgI
△ AgI – NaI
○ AgI – NH4I
EFFECTIVE NUCLEI /Gm AgI
10^15
10^14
10^13
10^12
10^11
10^10
-5
-10
-15
-20
TEMPERATURE (°C)

FIGURE 2

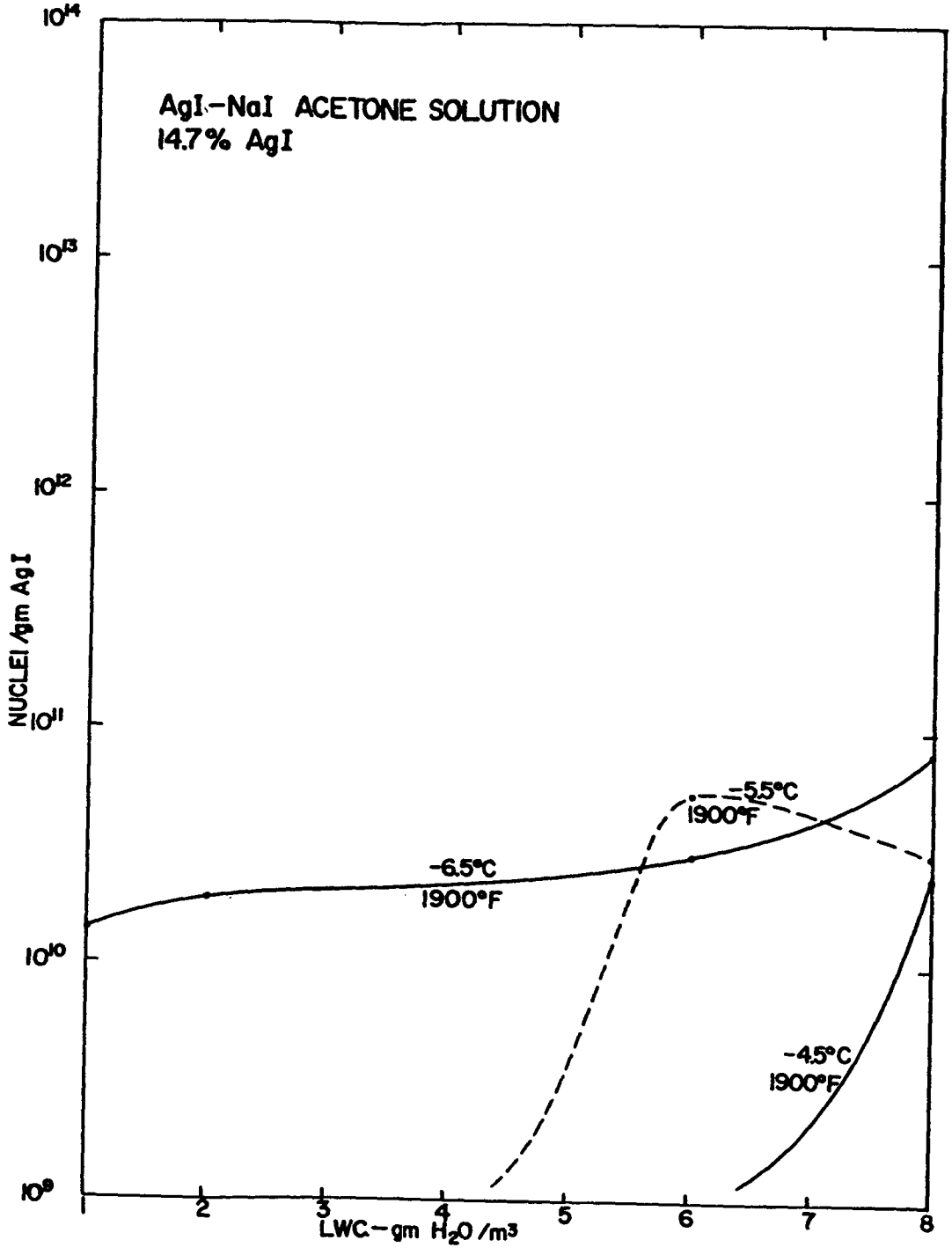

AgI-NaI ACETONE SOLUTION
14.7% AgI
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
NUCLEI/gm AgI
-5.5°C
1900°F
-6.5°C
1900°F
-4.5°C
1900°F
2
3
4
5
6
7
8
LWC-gm H_2O/m^3

FIGURE 3

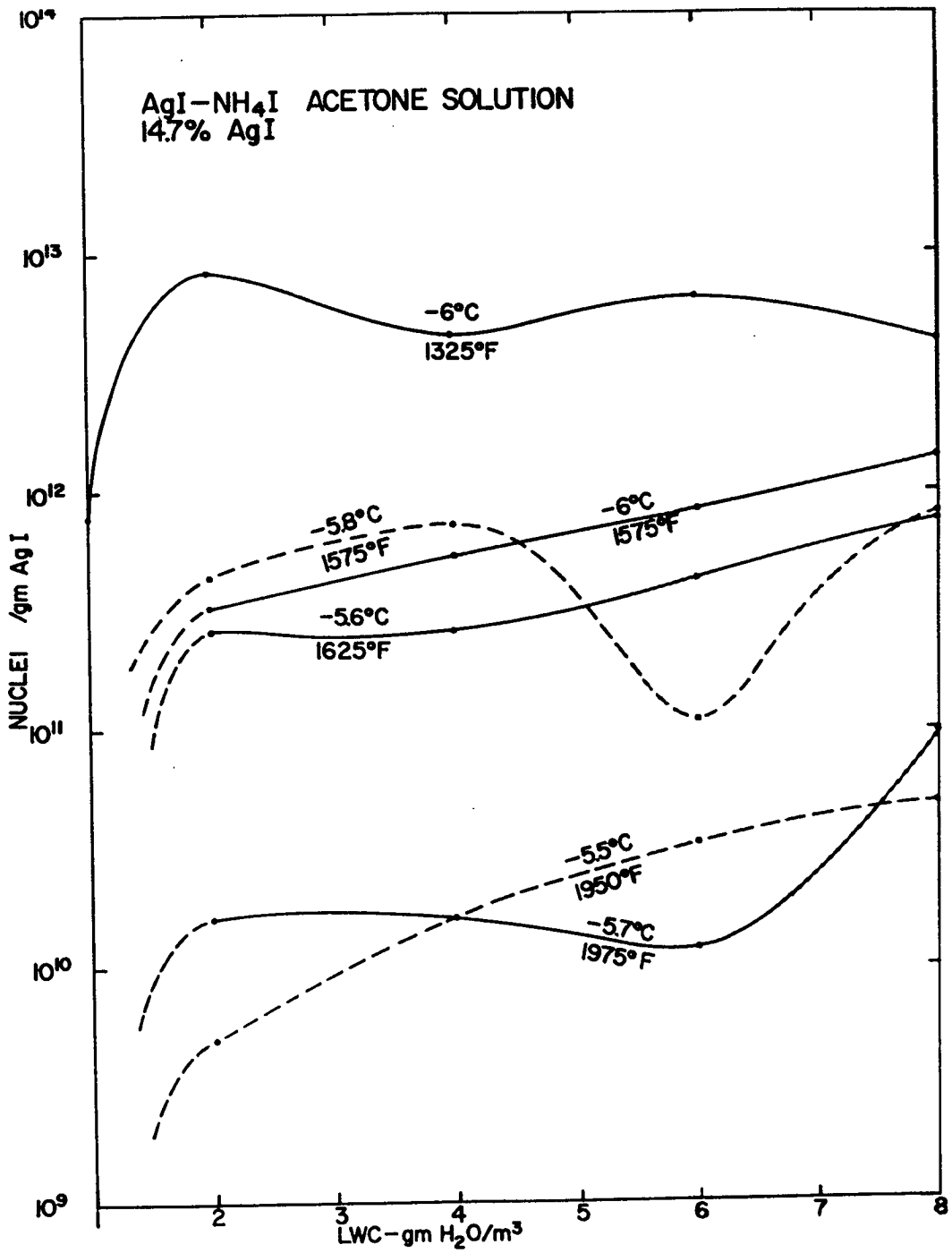

AgI–NH4I ACETONE SOLUTION
14.7% AgI
NUCLEI /gm AgI
LWC–gm H2O/m3
-6°C
1325°F
-5.8°C
1575°F
-6°C
1575°F
-5.6°C
1625°F
-5.5°C
1950°F
-5.7°C
1975°F

FIGURE 4

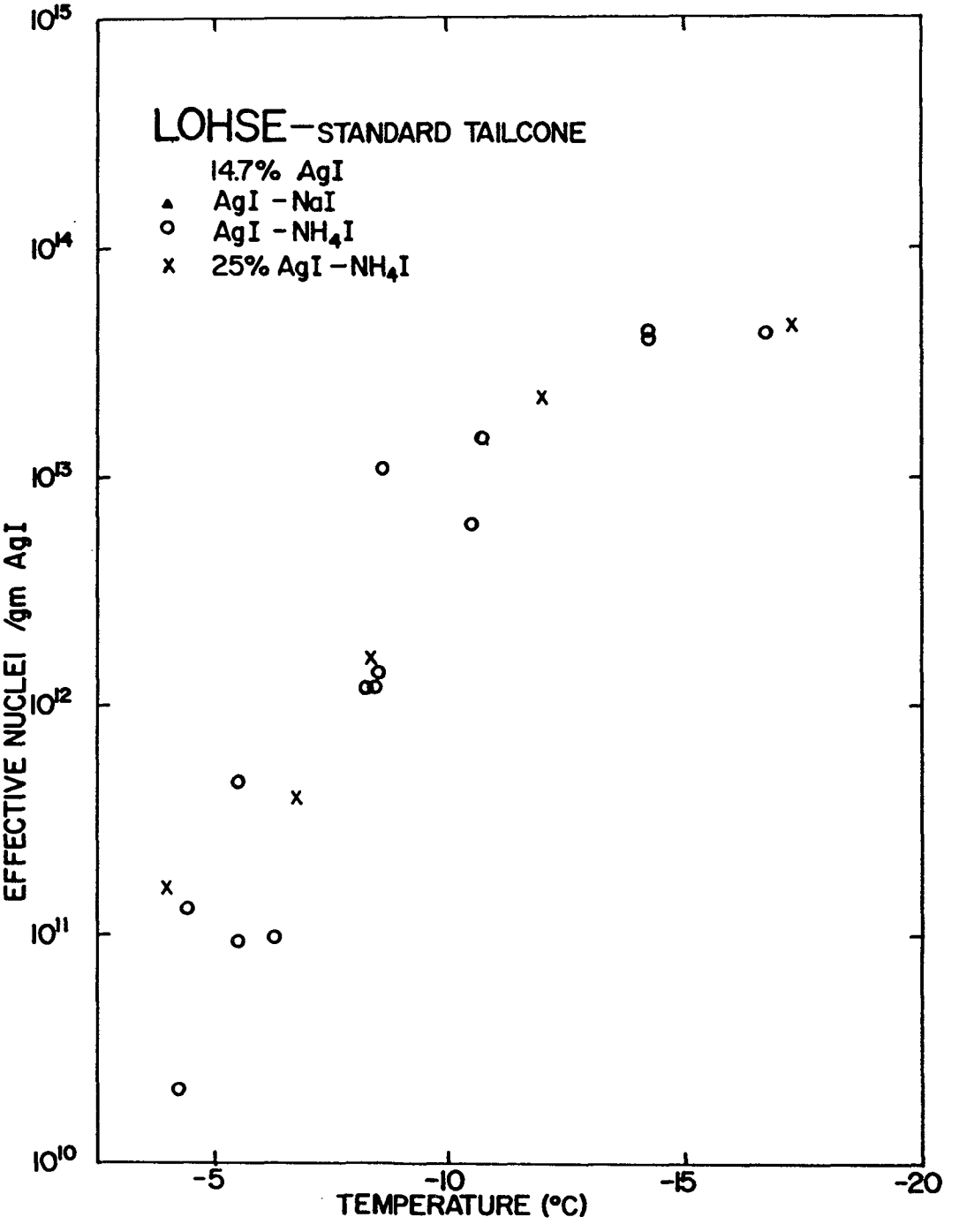
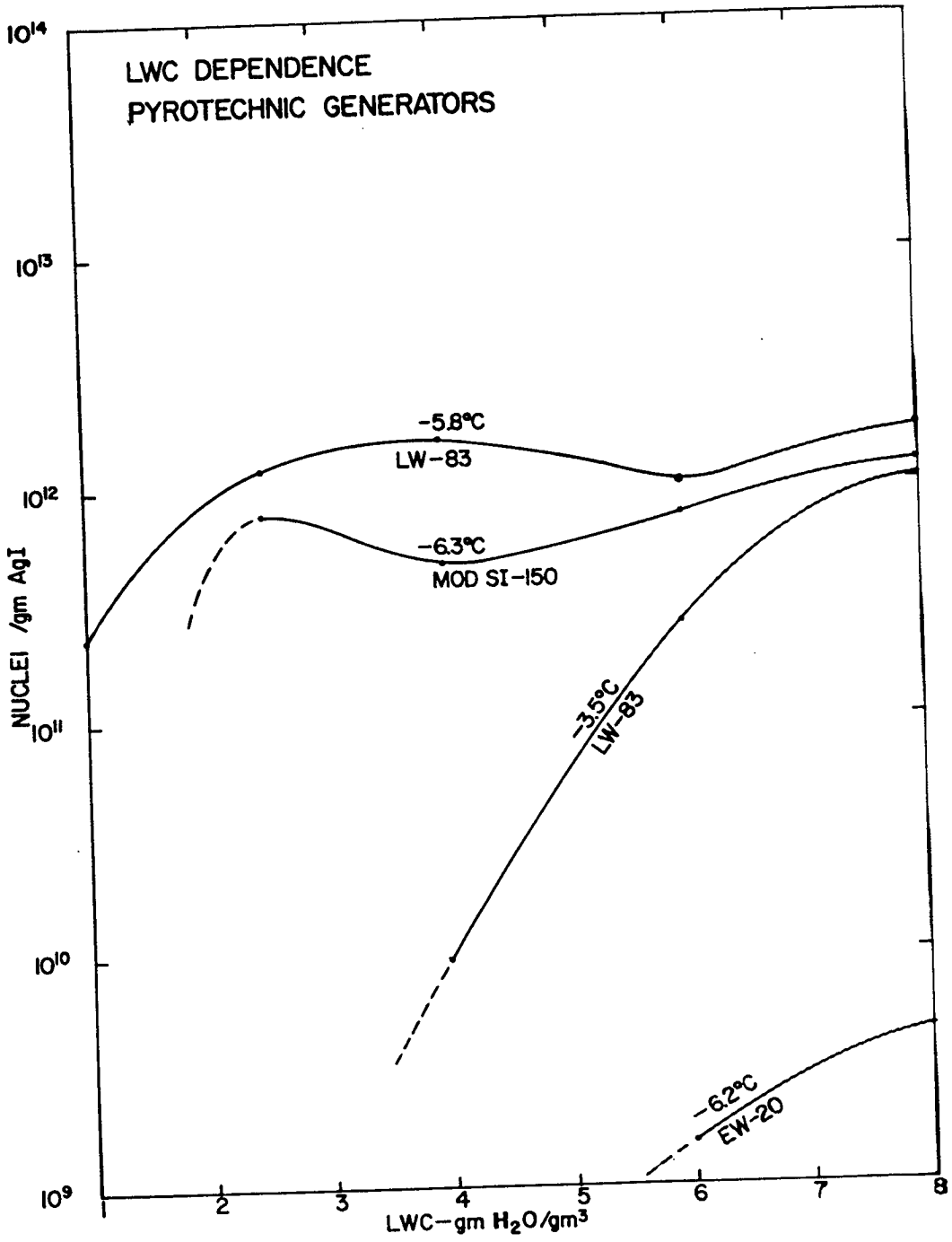

LOHSE—STANDARD TAILCONE
14.7% AgI
AgI - NaI
AgI - NH4I
25% AgI - NH4I
EFFECTIVE NUCLEI /gm AgI
10^15
10^14
10^13
10^12
10^11
10^10
-5
-10
-15
-20
TEMPERATURE (°C)

FIGURE 5


LWC DEPENDENCE
PYROTECHNIC GENERATORS
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
NUCLEI /gm AgI
-5.8°C
LW-83
-6.3°C
MOD SI-150
-3.5°C
LW-83
-6.2°C
EW-20
2
3
4
5
6
7
8
LWC-gm H_2O/gm^3

OPERATIONAL FORECASTING FOR PROJECT SIERRA CUMULUS*

Donald E. Lehrman
Fresno State College Foundation
Atmospheric Water Resources Research

I INTRODUCTION

Based on the concept that the development of improved water supplies through weather modification would require a year-around approach, a project was initiated to investigate the potential for increase from summer precipitation occurrences over the high mountain portions of the Southern Sierra Nevada by the Fresno State College Foundation under Bureau of Reclamation Contract No. 14-06-D-5819. The project was designed in a stepwise manner to investigate the problem through a series of theoretical studies involving historical data and field experiments involving aircraft cloud seeding activities. A significant portion of the research was devoted to the development of operational criteria which could be used by water resources agencies without the beneifit of specialized observing equipment or data sources. The development of a forecast technique which would require only standard Weather Bureau data to provide information on the occurrence of summer cumuli formed a part of these studies. The development of this forecast tool is the subject of this paper.

II SUMMARY

One of the ultimate goals of the summer program was to develop methods which would aid in determining those periods and conditions of high potential for increased usable water resulting from seeding the convective clouds which occur over the Southern Sierra in the summertime. Hydrologic studies have shown that the only consistent runoff producing situations have been from the more general storms, and that strictly isolated showers offer the least potential for good runoff production from larger areas[1]. Thus, AWRR embarked on a study to develop a statistical model to aid predicting the occurrence of general convective storms in the Southern High Sierra. The preliminary model was designed to provide a forecast from the morning upper-air observations. This forecast model was intended to provide merely an input to the decision-maker, not to act as the sole basis for an operational decision.

The primary statistical technique utilized for the study was a discriminant analysis for two groups[2]. The two groups or categories were: 1) days with general convective activity in the area of interest and 2) days with either isolated or no activity. The unit of observation was one day. Routine upper-air observations from 4 ESSA-Weather Bureau Stations, which were selected such that the operating area was essentially surrounded, served as the independent variables in the analysis. In this manner, an attempt was made to insure that air mass characteristics were always measured upwind from the project area.

The data appears to lend itself well to a discriminant analysis. The subsequent discriminant function derived by the analysis was statistically significant at the .999 level by the F-ratio test[2]. The results from testing the model indicate that the two categories of weather could be discriminated and consequently forecast. Although the model was developed with a specific purpose in mind, there are obvious uses of this tool beyond the field operations of AWRR. The model could be a valuable aid to both water runoff forecasts and local area weather forecasts, which are issued routinely by the Weather Bureau for the public and for the National Park and Forest Service personnel concerned with weather-induced fires.

*Summary of paper presented at 3rd Conf. on Weather Analysis and Forecasting of the American Meteorological Society.

III TECHNICAL DISCUSSION

A. Base Data

Data from June through September of 1967 and 1968 were used for the development of the preliminary model. Unfortunately, complete data was only available for this relatively short period. Each day was subjectively placed in one of the two categories after consideration of standard and specialized surface observations from Valley and mountain stations. The independent variables used in the study were selected from the 12Z rawinsonde observations from 4 ESSA-Weather Bureau stations. They were 1) Yucca Flat, Nevada (AEC or UCC), 2) Oakland, Calif. (OAK), 3) San Diego, Calif. (MYF), and 4) Yuma, Ariz. (YUM).

The variables from observations used in the analysis include: the 700 mb and 500 mb temperature, temperature-dewpoint spread, and wind; the precipitable water and the Showalter Index for all four stations. The input data is not subjective, and two people would extract exactly the same values from the data.

B. The Analysis

The values of the variables were used directly in the analysis with the exception of wind direction. It was necessary to express wind direction in a quantitative manner. To accomplish this, each wind direction was reduced to one of the eight possible forty-five degree sectors of the circle. The number of occurrences of wind direction in a sector on "GO" days (days on which general convective activity occurred) was divided by the total number of occurrences of wind direction in that sector for the entire base period (June-Sept., 1967-1968), resulting in a frequency in percent for each station at both 500 and 700 mb levels.

The purpose of the multivariate discriminant analysis used in the study was to provide a basis for classification of a particular day into one of two categories; either a day of general convective activity in the operating area (Group 2) or a day with isolated or no activity (Group 1) for any specified set of meteorological conditions. The calculated discriminant function provides the best separation of the two populations. That is for larger values of the discriminant function, the days tend to fall into Group 1, and for smaller values of the discriminant function, the days tend to fall into Group 2. Given this basis of classification, the probability of a day being in "Group 2" can be determined through a consideration of Bayes' Theorem[3].

Seven variables were chosen as significant in the analysis and yielded the following discriminant function and corresponding probability curve(Fig.1).

$$I = 59x_1 - 19x_2 - 1683x_3 + 122x_4 - 25x_5 + 56x_6 + 98x_7$$

Where

x_1 = AEC 500 mb Temperature-dewpoint spread

x_2 = AEC 500 mb Wind Direction

x_3 = AEC Precipitable water

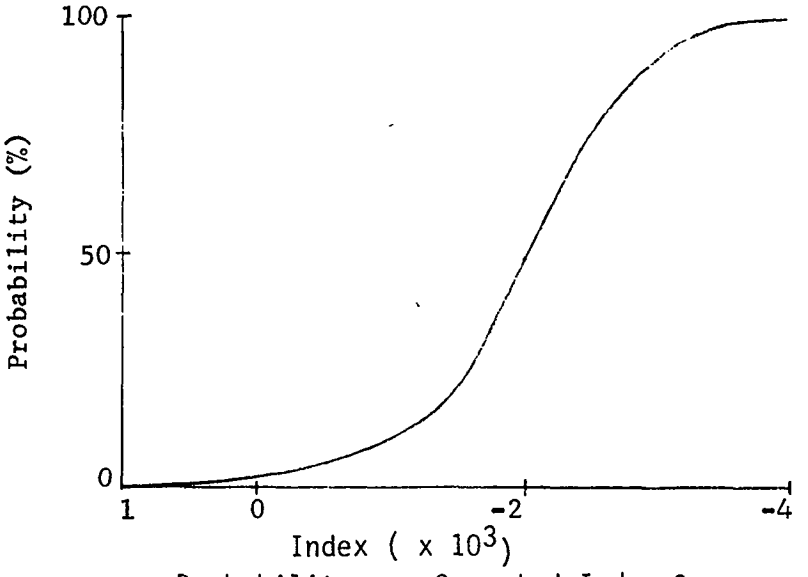
x_4 = OAK 500 mb Temperature

x_5 = OAK 500 mb Wind direction

x_6 = OAK Stability Index

x_7 = YUM 700 mb Temperature

FIGURE 1



Probability vs. Computed Index Curve
Sierra Cumulus

WIND DIRECTION TRANSFORMATION

Direction (Deg)	X_2	X_5
001 - 045	28	18
046 - 090	68	63
091 - 135	66	66
136 - 180	56	69
181 - 225	22	19
226 - 270	18	15
271 - 315	8	11
316 - 360	25	38
Calm	0	0

The individual terms behave as expected from physical reasoning and have been considered important by local forecasters with one exception. The significance of the 700 mb temperature at Yuma was not obvious. Variables x_1, x_2, x_3, x_5 all behave in a way that is representative of the normal situation for summertime convective storms in the High Sierra, which is moisture drawn from the Gulf of Mexico. The variables x_4 and x_6 most probably represent the early and late summer organized systems moving to the area from the Pacific, generally characterized by either an upper-level trough or closed low passage in the vicinity of the operating area. However, the relative importance of the 700 mb temperature is not explicit. The warm-moist air from the Gulf is normally sensed above 700 mb at Yuma and only the wind direction was considered important at that level. However, the analysis chose the 700 mb temperature as being significant. Furthermore, as the 700 mb temperature at Yuma decreases, the probability of a "Group 2" occurrence increases. This temperature variation appears to be attributable to the position relative to Yuma of the 700 mb High dominant over the Western States during the summer months.

To test the relative importance of each term in the discriminant function, a comparison of the resulting F - statistics were made as one variable at a time was removed from the original equation, and the equation with the remaining terms tested for statistical significance. The results are presented in Table I.

TABLE I

Variable Removed	F-Ration (6,231)
OAK 500 mb Wind Direction	30.5
OAK 500 mb Temperature	33.1
AEC 500 mb T - Td	34.2
AEC 500 mb Wind Direction	34.6
YUM 700 mb Temperature	34.9
AEC Precipitable Water	35.2
OAK Stability Index	37.0

C. Model Evaluation

Data from June and July 1969 were used to evaluate the preliminary model. On the basis of observations from mountain and valley stations, each day was categorized into one of the two previously stated groups of weather, and then compared with the corresponding probability forecast. The effectiveness of the model in classifying the members of the two categories was evident. The most desirable result, of course, would have been perfect separation of the two populations. This degree of separation was not achieved but the discrimination between the two groups was nevertheless apparent.

It is difficult to quantitatively assess the model, since the forecast is presented in terms of probabilities rather than in absolutes. The probability forecast must be evaluated by the decision-maker in terms of his own operations. If, for example, the decision for AWRR operating was based solely on a predicted 20% probability or greater of the occurrence of suitable cloud conditions, the net result for the period of evaluation during 1969 would have been one opportunity lost and on three occasions the cloud conditions would not have been suitable for operations. These results are sufficient for this type of operation and the period chosen to test the statistical forecast tool appears to be representative of the situations which create the general convective activity occurences in the So. Sierra Nevada during the summer months. On the other hand, the decision to alert lookouts and fire fighters to possible weather-induced fires based on the probability forecast might require that different criteria be established to insure satisfactory operations.

D. Extended Forecasts

Although the present forecast model is designed to use the 12Z rawinsonde observations of the day in question for input, longer-ranged forecasts are possible if the various terms of the discriminant function can be forecast with a reasonable degree of accuracy. On the other hand, extended forecasts are also possible using the same statistical techniques as were used in the original model, to develop a new discriminant function; one derived from using data twelve, twenty-four, or thirty-six hours previous to the day being considered. Development of a model which will forecast the probable weather twenty-four hours in advance is well underway at AWRR.

IV CONCLUSIONS

The discriminant analysis was successful in providing a basis for the classification of the two categories of weather and consequently could be forecast. The resultant forecast is presented in operational terms, and provides advance information on the occurrence of general convective cloud activity over the AWRR project area in the summer months. On the basis of the probability forecast, it appears that operating criteria can be established satisfactorily. Furthermore, this information is provided without the need of specialized observing equipment or data sources.

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TRACE SILVER ANALYSIS IN WATERS COMBINING SOLVENT EXTRACTION WITH THE ATOMIC ABSORPTION MICROSAMPLING BOAT

by

Howard A. Salman

United States Department of the Interior
Bureau of Reclamation
Denver, Colorado

ABSTRACT

A fast and accurate chemical technique was developed for the trace analysis of silver in water. The method is an aid in evaluating the effectiveness of AgI cloud seeding material by measuring the concentration of Ag in the resulting atmospheric precipitation. The analysis can be performed near the precipitation collection site and would eliminate the cost of freezing and shipping samples. Subnanogram quantities of silver are extracted from water by a solvent-extraction technique using an organic-complexing agent. The silver content is determined by using an atomic absorption spectrophotometer with a microsampling boat accessory. The procedure can determine Ag in concentrations as low as 5 parts per trillion with an error in reproducibility within 5 percent.

INTRODUCTION

A valuable aid in the evaluation of the effectiveness of cloud seeding methods and seeding agents is the detection of the cloud seeding material in the resulting precipitation. Ideally, the most desirable technique would be one in which the cloud seeding material could be detected accurately in subnanogram quantities and analyzed as quickly as possible at a facility near the collection site. Since AgI is a major cloud seeding material, a trace analysis method for the detection of Ag has been developed to meet these criteria.

Several sensitive methods have been developed which can detect Ag in the subnanogram range. The method of Warburton and Young[1], using ion-exchange extraction and neutron activation analysis, is one of the more sensitive. Parungo and Robertson use organic solvent extraction followed by atomic absorption analysis to reach a silver detection limit of 1×10^{-11} gml^{-1}. West and Williams, using solvent extraction with atomic fluorescence spectroscopy, have reported a detection limit of 4×10^{-11} gml^{-1}.

In order to determine accurately the Ag concentration in weather precipitation, the background silver concentration must be known. Parungo and Robertson report many values which were below the sensitivity of their analysis. Warburton and Young report unseeded snow samples having less than

$1x10^{-11}gml^{-1}$. It was desirable, therefore, to develop a technique whose accuracy was within 10 percent at 10^{-11}-$10^{-12}gml^{-1}$. Also, cost and rapidity were important factors to consider.

It has been shown that Ag will be absorbed onto container walls within a relatively short period of time, thus requiring either a fast analysis time or a method of preserving the sample. At present, freezing the samples has been chosen as the method of preservation, although complexing agents have been added in order to stabilize silver in solution for a period up to 10 days. The technique developed in this report may be used near the collection site thus eliminating the necessity and expense of freezing or shipping the samples.

Recently a microsampling boat for the atomic absorption spectrophotometer was developed by Kahn, et. al. This technique improved the detection limit for silver to $10^{-10}gml^{-1}$. The results and conclusions in this report have been obtained by coupling organic solvent extraction with the atomic absorption microsampling boat.

SUMMARY AND CONCLUSIONS

A weather modification program using AgI as the cloud seeding agent requires the subnanogram analysis of silver in the resulting precipitation.

Water containing trace amounts of silver is first analyzed with the atomic absorption spectrophometer microsampling boat. If no silver is detected, the water is then extracted with methyl isobutyl ketone and ammonium pyrrilodine dithiocarbamate at a pH of 1.30 to 1.90. One milliliter of the organic phase is evaporated in a microsampling boat, and flashed on the atomic absorption spectrophometer. Silver solutions containing as low as $5x10^{-12}gml^{-1}$ Ag were analyzed with an error in reproducibility within 5 percent.

APPLICATION

The chemical technique developed in this report should be a valuable aid in furthering the technology of weather modification as it applies to precipitation increase and redistribution.

This technique can be performed near the precipitation collection site, and would eliminate the cost of freezing and shipping samples.

Analysis as described in this report would allow weather modification personnel to evaluate the effectiveness of cloud seeding techniques much faster than present analytical methods.

RESULTS AND DISCUSSION

Typical standard curves for a trace silver analysis using the

direct boat technique, and organic solvent extraction coupled with the boat technique, are shown in Figures I and II, respectively. It should be noted that the distilled water used for the preparation of silver standards contained approximately $2x10^{-12}gml^{-1}$. This was the natural background level of the distilled water source. All other reagents used contained less than $1x10^{-12}gml^{-1}$. The peak height obtained upon extracting the zero standard was subtracted from the peak heights of the other standards. However, this value should not be subtracted from any unknown samples extracted.

The greatest source of error in these analyses is in the silver contamination of glassware and of the analyst's contamination of the boat. Meticulous laboratory procedures must be used in order to obtain reproducibility. Glassware was soaked overnight in dichromate-sulfuric acid cleaning solution and rinsed with 1:1 HNO_3, followed by distilled water. Soaking in 0.1 N KCN, followed by overnight soaking in a saturated solution of EDTA (ethylene diamine tetraacetic acid, disodium salt), did not improve the removal of silver from the separatory funnels. Three 125-milliliter separatory funnels were soaked in cleaning solution, 0.1 N KCN, and saturated EDTA, respectively. After rinsing with 1:1 HNO_3 and distilled water, a blank extraction using the APDC-MIBK extraction procedure, followed by atomic absorption spectrophometry (AAS) boat analysis, was determined. Figure III shows that this procedure did not remove completely or reproducibly all of the silver from the separatory funnels. However, after a second extraction was made on the same separatory funnels, the peak heights obtained approach the normal background level (Figure IV). Thus, in order to assure that the separatory funnels are free of silver, they must first undergo the cleaning process, followed by blank extractions, until a background peak height is obtained.

At scale expensions of 30X, the handling of the boat becomes a problem. For instance, if one has touched any silver coins or has a silver ring on his finger, the silver may be transferred to the boat, and subsequently appears as a peak when the sample is flashed. The hands should be washed thoroughly and rinsed with distilled water before each handling of the boat. The use of nichrome tongs in handling the boat is difficult when the boat is loaded; however, they are used to remove the boat from the oven after evaporation.

The extraction efficiency of silver using APDC and MIBK is a function of the pH of the solution. Figure V shows the recorder response at 3X after various amounts of concentrated HNO_3 were added to 100 milliliters of a0.01 PPM Ag solution. Before the pH measurement, 0.2 percent APDC was also added. Thus, the pH of the samples when extracted should be in the pH range of 1.30 to 1.90.

A temperature of 280^{o} C was chosen for the evaporation temperature. This allows one to flash a sample within 5 minutes after placing in the oven. Figure VI shows that the removal time from the oven is not critical between 5 and 10 minutes, Peaks 1 and 2, respectively.

Parungo, etal., of EG&G Incorporated, have recently analyzed

seeded snow samples for the Bureau's Office of Atmospheric Water Resources. In order to check the accuracy of this technique, Parungo prepared water samples of known silver concentration for our analysis. Table 1 shows the results of these tests. Since the samples were analyzed 24 hours after preparation without prior preservation, absorption on container walls must be considered a possible source of error. West, et. al. have reported that the rate of absorption of silver on polyethylene surfaces decreases as the silver concentration decreases. Therefore, if absorption did occur, the most concentrated sample should have the greatest percent error. Table 1 shows this is indeed the case as Sample C ($1x10^{-9}$ gml^{-1}) has a 55 percent error compared to 0.0 percent for Sample A ($1x10^{-11}$ gml^{-1}). The error in reproducibility of the direct boat technique is well below 5 percent as shown in Figure VI. Since Sample C was analyzed by the direct boat method, the large error observed was most probably due to absorption on the container surface.

PROCEDURE

Apparatus:

All experimental work was performed with normal laboratory equipment including the following:

Atomic Absorption Spectophotometer:
Perkin-Elmer Model 303 with a three-slot Boling burner, a silver hollow cathode source, and a microsampling boat attachment. Instrument settings were: lamp current - 12 milliamperes; wavelength - 3,281 Å; exidizer - air (flow setting-5.0); fuel-acetylene (flow setting-5.0); Slit-4; scale-10X-30X; noise suppression-1.

Recorder:
Perkin-Elmer Model 165, 10 millivolt full-scale response, less than 1 second full-scale span, chart speed - 10 millimeters per minute.

Reagents:

MIBK: (Eastman) Methyl isobutyl ketone.
Purified by shaking 90 milliliters of MIBK with 10 milliliters of distilled water. Figure 7, Peak 1, shows the peak height from 1 milliliter of evaporated MIBK after this treatment using the microsampling boat. Peak 2 shows the peak height before this treatment.

APDC: (Ammonium pyrrilodine dithiocarbamate).
Prepare a standard solution containing 0.2 gml^{-1}. One milliliter is used for every 100 milliliters of sample extracted. The chelating agent was prepared according to the procedure of Pereira. When a commercial product (K & K Laboratories) was compared to the prepared reagent, a much higher blank value was observed. Since this technique depends upon a low blank value, the commercial product could not be used.

$AgNO_3$:
Baker reagent, 99.7 percent assay. The reagent was dried at 100^{o} C and a stock solution prepared containing $1 mg ml^{-1} Ag+$. All standard silver solutions were prepared by diluting the stock solution with distilled water and used within 2 hours of preparation.

HNO_3: 0.2 milliliters of reagent grade Dupont acid gave a peak height of 1.6 at 30X scale expansion. This is small enough to consider as zero.

Experimental Method:

Since the detection limit of Ag using the microsampling boat is only $10^{-10} gml^{-1}$, a concentration step must be used. Seeded snow and rain samples, however, may not require this concentration step.

One milliliter of each unknown is placed in a microsampling boat, evaporated to dryness, and flashed at 10X scale expansion using (AAS). If a peak is not observed, the sample is extracted as follows: Place 100 milliliters of sample in a 125-milliliter separatory funnel. Add 1 milliliter of APDC (ammonium pyrrilodine dithiocarbamate) standard solution while swirling. After 1 minute, add 0.2 milliliter of concentrated nitric acid. Shake and allow to stand for 5 minutes. Then add 5.0 milliliters of water-saturated MIBK (methyl isobutyl ketone). Place on a mechanical shaker for 15 minutes. Allow the phases to separate for 5 minutes and drain off the lower phase. Using a 1-milliliter long-tipped pipette, remove 1 milliliter and place in a previously heated sampling boat. Evaporate in a 280^{o} C oven for at least 5 minutes. Remove the boat from the oven, place in the sampling boat holder, and flash on the AAS at 30X scale expansion. Record the peak height. During the extraction procedure, extract silver standards of zero, $5x10^{-12}$, and $10x10^{-12} gml^{-1}$. For the direct boat analysis, prepare silver standards of $5x10^{-10}$ and $10x10^{-10} gml^{-1}$. Plot the peak height of the standards versus the Ag concentration in gml^{-1}.

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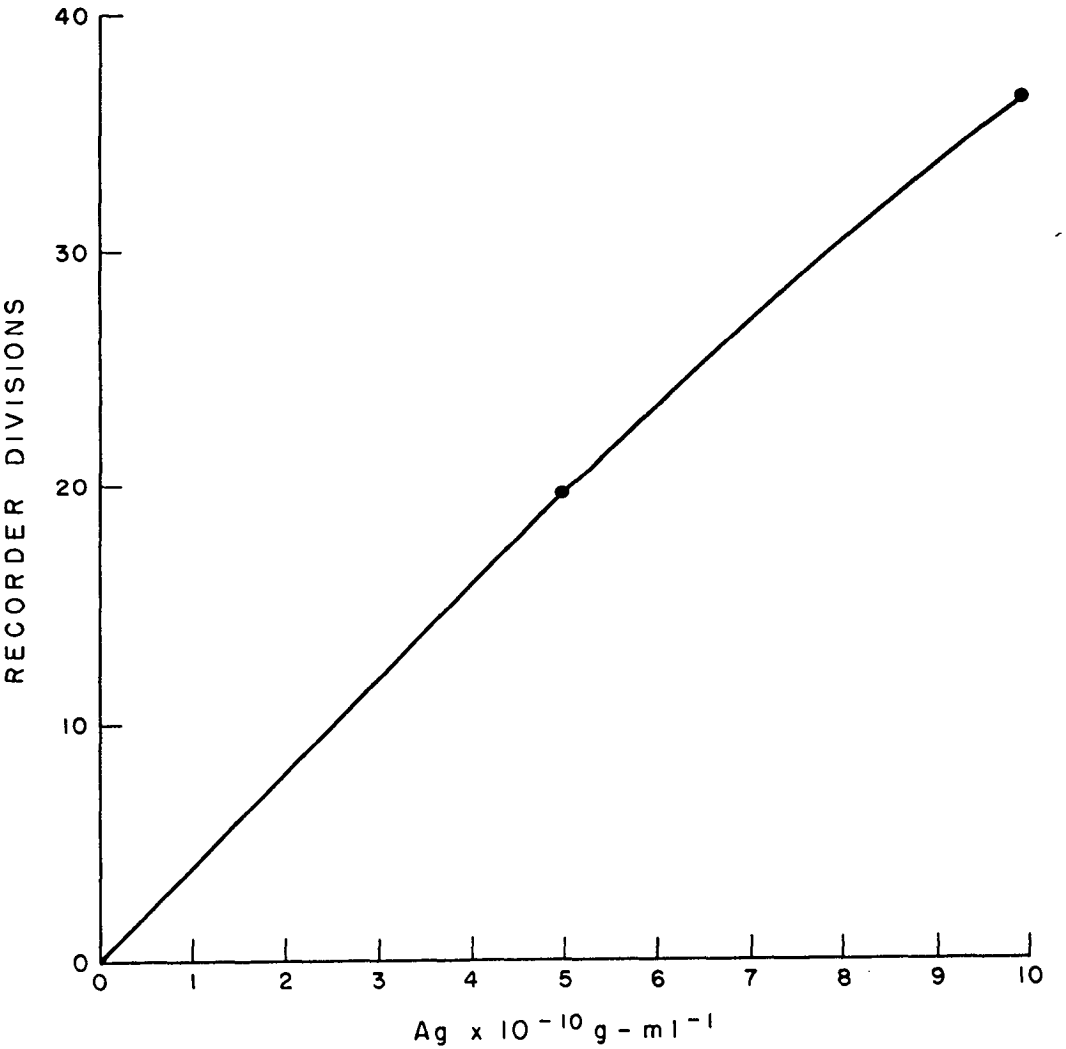


FIGURE I - STANDARD CURVE FOR Ag, NOT EXTRACTED
10X SCALE EXPANSION

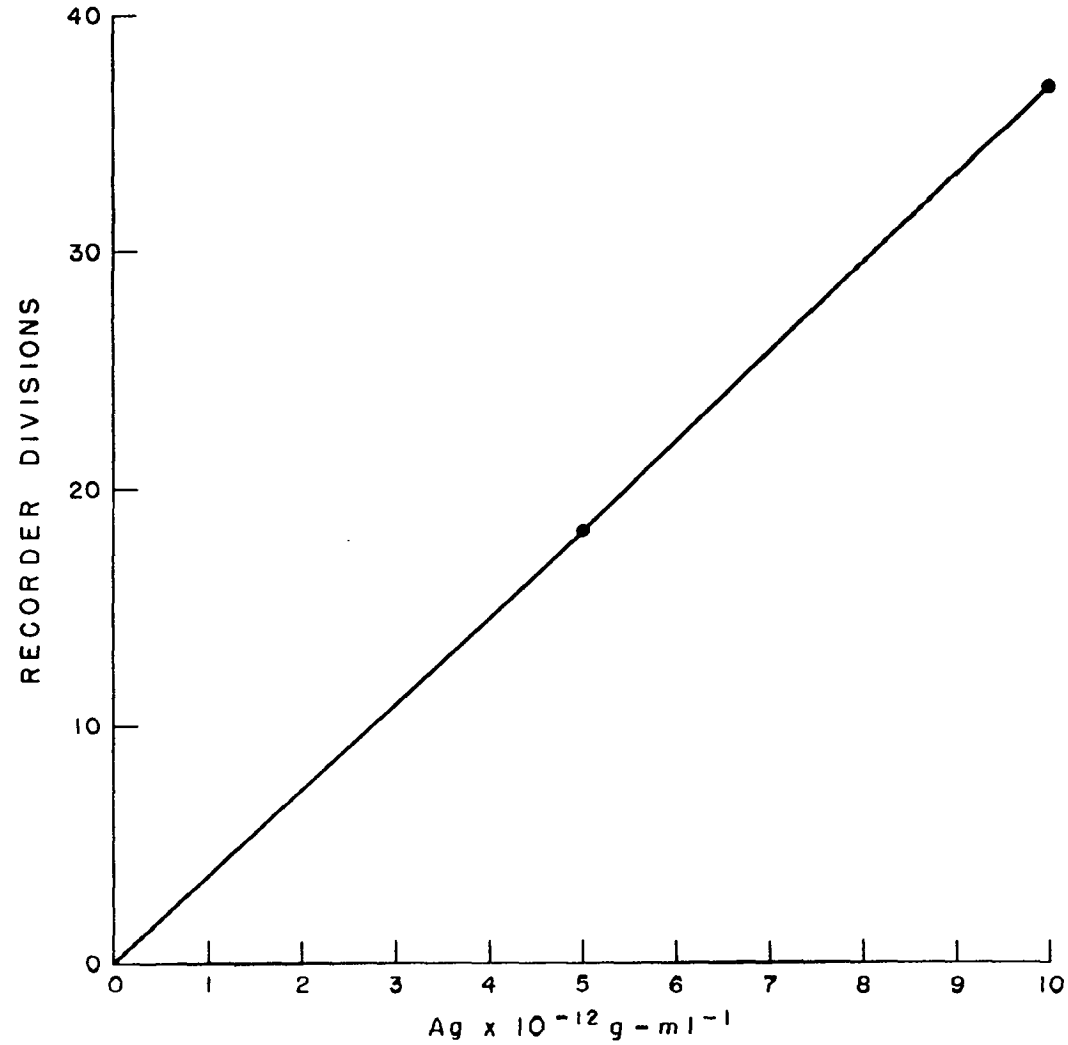


FIGURE II - STANDARD CURVE FOR Ag, EXTRACTED.
30X SCALE EXPANSION

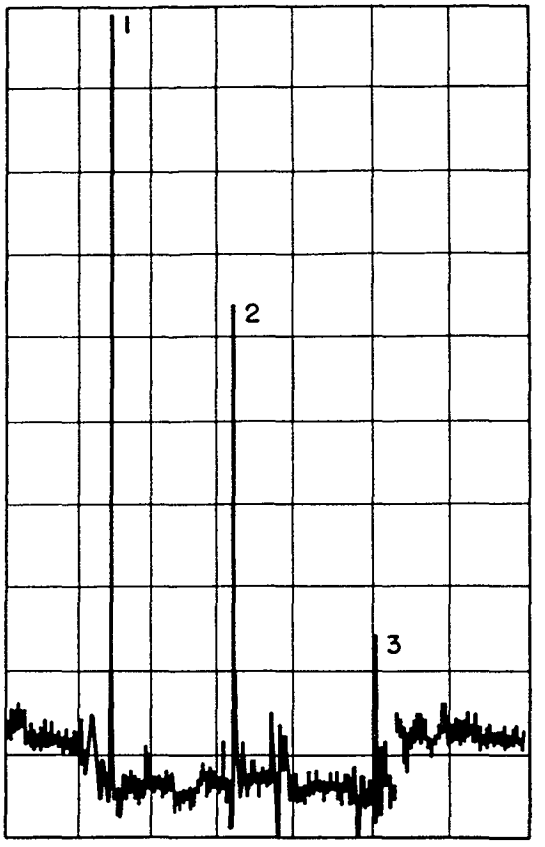


FIGURE III - FIRST EXTRACTION OF THREE SEPARATORY FUNNELS AFTER CLEANING IN H_2SO_4 - DICHROMATE CLEANING SOLUTION, .1NKCN, AND SAT'D. EDTA. 10X SCALE EXPANSION.

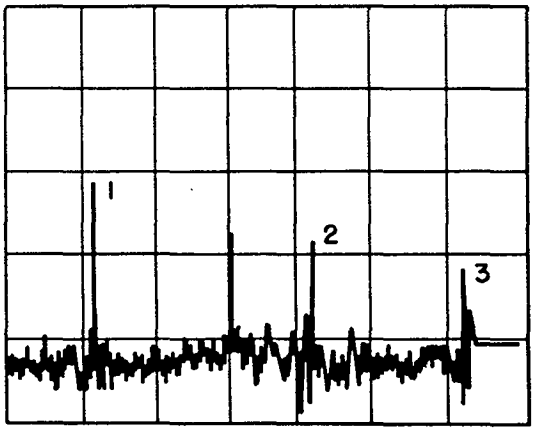


FIGURE IV - SECOND EXTRACTION OF THE SEPARATORY FUNNELS FROM FIGURE III 10X SCALE EXPANSION

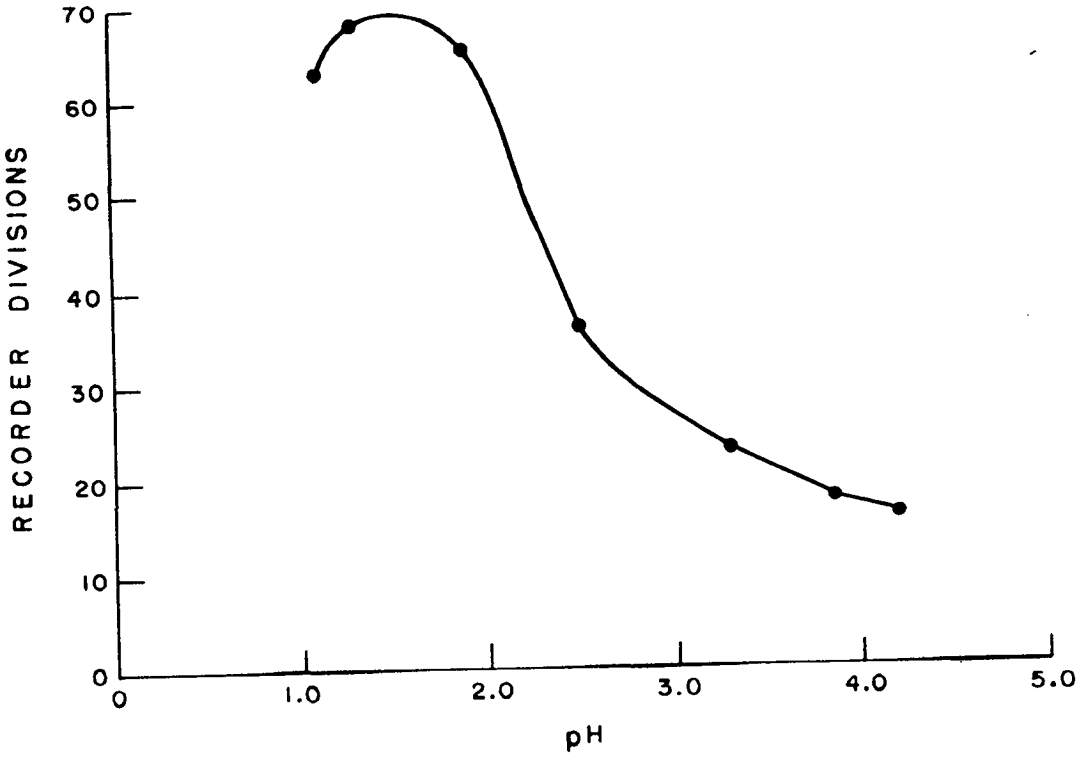


FIGURE V - EXTRACTION EFFICIENCY VERSUS pH
3X SCALE EXPANSION

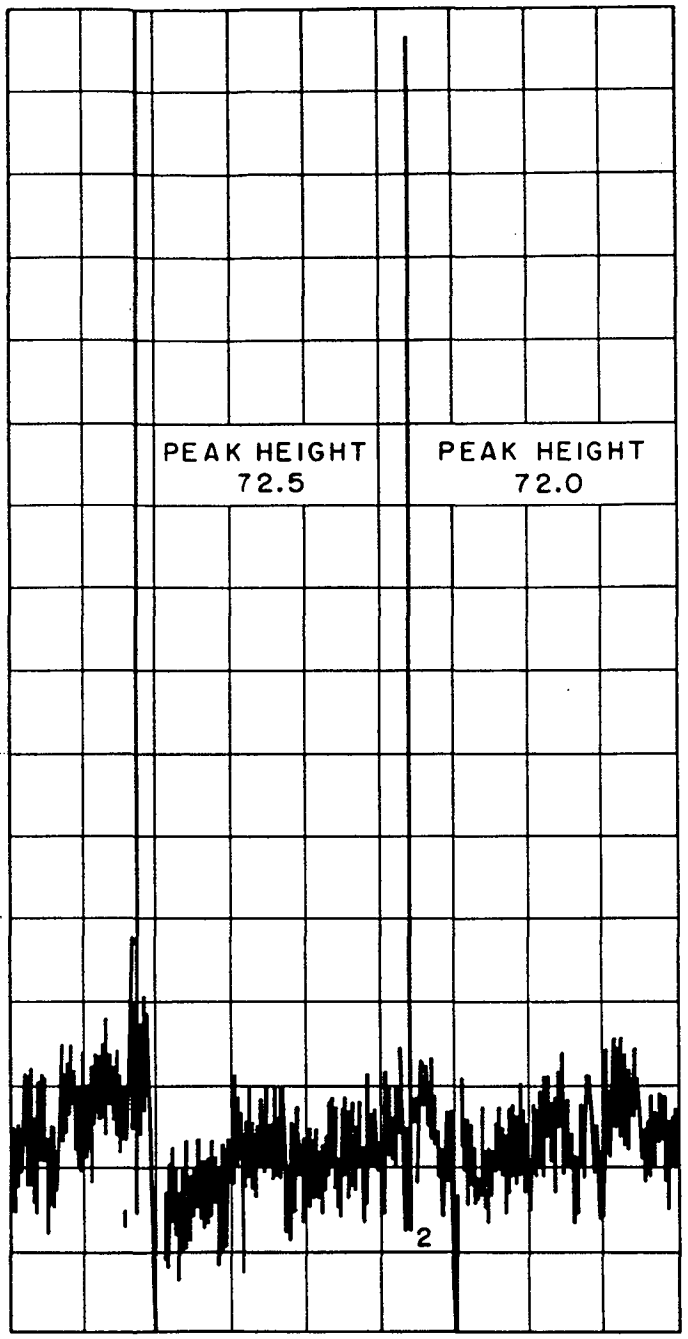


FIGURE VI - ONE ML. OF 1 x 10^{-11} gml^{-1} Ag AT 30X USING THE MICRO SAMPLING BOAT. NO.1 = 5 MIN. AT 280° C; NO. 2 = 10 MIN. AT 280° C.

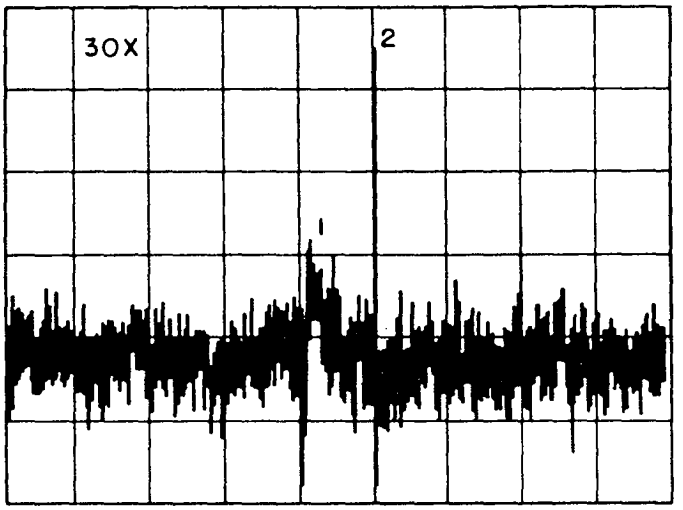


FIGURE VII - DIRECT BOAT ANALYSIS FOR Ag USING ONE ML. OF MIBK: PEAK I - PURIFIED BY SHAKING WITH DISTILLED H_2O; PEAK II - AS RECEIVED FROM SUPPLIER.

TABLE I

DETERMINATION OF SILVER IN WATER

SAMPLE NO.	METHOD	EXPERIMENTAL Ag (gml^{-1})	REPORTED Ag (gml^{-1})	% ERROR *
A	EXTRACTION-BOAT	1.0×10^{-11}	1×10^{-11}	0.0
B	EXTRACTION-BOAT	9.6×10^{-11}	1×10^{-10}	4.0
C	DIRECT BOAT	4.5×10^{-10}	1×10^{-9}	55.0

$$* \% \text{ Error} = \frac{\text{Reported Ag}(gml^{-1}) - \text{Experimental Ag}(gml^{-1}) \times 100}{\text{Reported Ag}(gml^{-1})}$$

A NEW METHOD OF AERIAL STEREOPHOTOGRAMMETRY

by

William J. King and Dale C. Hall

Weather Science, Inc.
Norman, Oklahoma

ABSTRACT

An effective method for determining the heights and locations of cloud-top features and measuring their growth and decay has been developed. The basic data for analysis is extracted from aerial photographs taken with side mounted, motor driven cameras. Flight parameters are recorded by a specially developed airborne digital data package. The aircraft flies a set course past the target cloud taking a series of photographs on each pass. From each series, a pair of photographs is selected for stereo analysis. This paper describes a new, computer-oriented stereophoto analysis method and its associated airborne digital data package.

1.0 INTRODUCTION

1.1 General

Stereoscopic photogrammetry dates back to the mid 1800's when photographs were first used for measuring purposes. Experiments in aerial photogrammetry date back to 1858, and most of the development of aerial procedures has been in the area of terrain mapping.

Aerial stereophotogrammetry has in recent years become a useful tool in cloud-top studies. In 1961, W. E. Howell & Associates developed the first aerial stereophotographic analysis method for use in weather modification research. The practicality of using an aircraft as a platform for cloud-top photographic observations, rather than using a ground-based camera, is discussed in some detail by Herrera-Cantilo (1969).

A series of stereophotographs not only provides valuable visual evidence of growth and decay of cloud top features but more importantly allows the researcher, using simple mathematical procedures, to determine the exact locations, sizes, and heights of specific cloud points. The basic analysis method is equally applicable to cloud base measurements when visibility is adequate for photography.

1.2 Definition of Terms.

1.2.1 Analog Digitizer.

This device is used to determine the absolute coordinate values of preselected points on a photograph. The photo is registered and taped to the digitizer board and various points of interest are individually located with a moveable arm which is connected to X and Y-axis potentio-

meters. The voltages from the potentiometers are converted to absolute digital units, and these X and Y values are punched onto computer cards.

The stereophotogrammetric principles, upon which many of the following definitions and concepts are based, are fully discussed by Hallert (1960).

1.2.2 Optical Axis of the Camera Lens.

The optical axis of the camera lens is the line through the focal point of the lens perpendicular to the plane of the film surface through the point at the geometric center of the negative. This relationship holds for any orientation of the camera.

1.2.3 The Airborne Stereo Cameras.

These two cameras, one pointed out each side of the aircraft, are mounted in such a way that their optical axes are co-linear. This common optical axis is oriented perpendicular to the vertical plane through the longitudinal axis of the aircraft at the point denoted the "optical center." Certain changes of attitude of the aircraft will cause a rotation of the common optical axis of the cameras about the optical center.

1.2.4 Roll.

Roll is rotation of the aircraft around its longitudinal, fore to aft, axis. Zero-roll implies a level attitude. Roll causes rotation of the common optical axis in a vertical plane through the optical center.

1.2.5 Pitch.

Pitch is rotation of the aircraft around its transverse, wing tip to wing tip, axis. Zero-pitch implies a level attitude. Pitch causes rotation of the film plane around the optical axis.

1.2.6 Yaw.

Yaw is rotation of the aircraft around the vertical axis through the roll-pitch center of the aircraft. Zero-yaw implies that the angle between the longitudinal axis of the aircraft and the aircraft flight path is zero degrees. Yaw causes rotation of the common optical axis in a horizontal plane through the optical center.

1.2.7 Stereo Pair.

The stereo pair is the two photographs selected for analysis from a stereo photo run. The two photographs must have been taken with the same orientation of the camera for both frames so that, when placed in stereo viewing configuration (Fig. 1), the pair will present a distortion-free, three-dimensional optical model of the target. Depending upon the analysis method employed, the stereo pair must be either a "zero-yaw pair" or a "zero-roll-yaw pair."

1.2.8 Zero-Yaw Pair.

The zero-yaw pair is the stereo pair that has zero-yaw relative to each other; i.e., the vertical plane through the optical axis of the lens forms the same angle with the vertical plane through the aircraft flight path for both frames of the stereo pair. In the ideal case, this angle will be 90 deg.

1.2.9 Zero-Roll-Yaw Pair.

The zero-roll-yaw pair is the zero-yaw pair that has the same roll angle for both photographs. In the ideal case, roll will be zero.

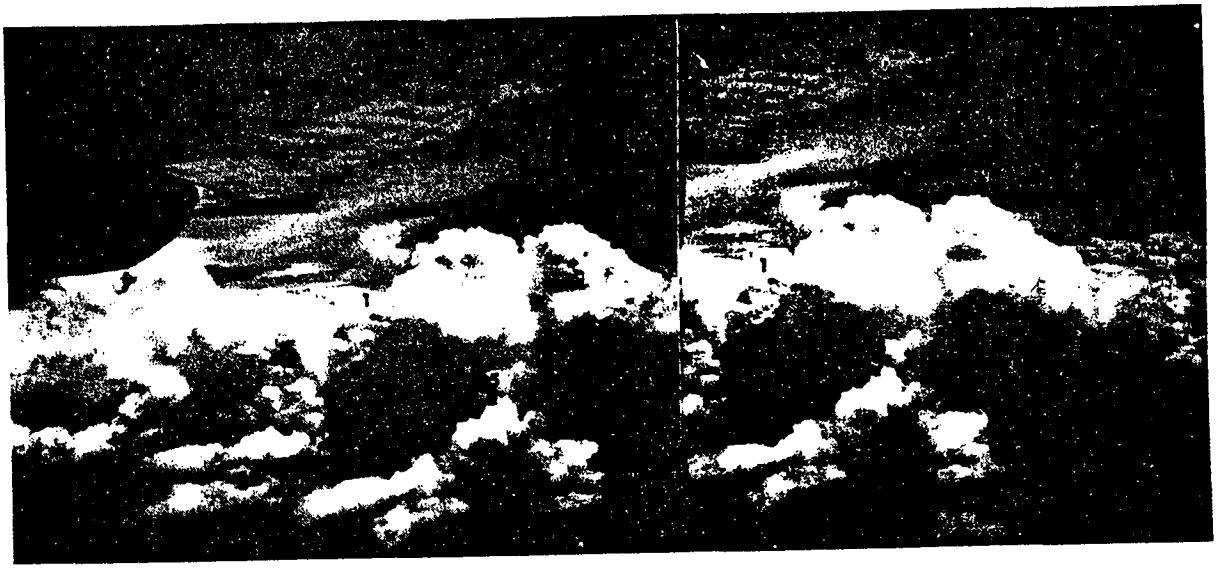


Fig. 1

Fig. 1. A zero-roll-yaw pair in stereo viewing configuration with points of interest labeled.

2.0 EVOLUTION OF THE WEATHER SCIENCE, INC., STEREOPHOTO ANALYSIS METHOD

2.1 The Original Method

In August 1967, Weather Science, Inc., developed a stereo analysis procedure for use on PROJECT HOTSHOT (Booker, Hart, Cooper, and Hall, 1968). This method worked basically as follows:

a) A series of photographs was made using an airborne, level-

mounted camera sighted 90 deg from the longitudinal axis of the aircraft. Each photograph was printed with 6X enlargement to include all frame edges and corners.

b) From the series, a pair of photographs with zero yaw relative to each other was chosen for analysis. This was the zero-yaw pair.

c) An aircraft horizon was then determined and inscribed on the zero-yaw pair.

d) Points of interest on the test cloud, identifiable on both frames of the zero-yaw pair, were then selected by the analyst and given location identifications on an analog digitizer.

2.1.1 The Data Output

Utilizing the digitized data from the zero-yaw pair, a computer was used to compute and print out values for distance from camera, height above sea level, distance from frame center, and scale factors for the selected cloud points (Table 1).

Table 1. Computer print-out for cloud feature analysis.

STEREO PHOTO ANALYSIS SERIES 0000 MISSION 01 DATE 12/17/69
STEREO DATA PACKAGE CALIBRATION CONTRACT

FRAMES 2 & 4 TAS 167K ALTITUDE 16500 MSL CAMERA HEADING 113 DEG.

CLOUD POINT (NO.)	DISTANCE FROM ACFT (NM)	HEIGHT (FT MSL)	DISP FROM VIEW FIELD CENTER (NM)	SCALE FACTORS (MM/1000FT)	(MM/KM)
1	5.75	17656.6	-1.72	6.32	10.74
2	5.83	19363.4	-1.68	6.24	20.46
3	5.23	18744.1	-1.32	6.95	22.79
4	7.62	18984.7	1.27	6.45	21.17
5	6.33	19089.3	1.78	6.01	19.65

END OF STEREO PHOTO SERIES 0000 ANALYSIS

2.1.2 The Original Program.

a) The distance to a selected cloud point was computed using ratio and proportion. Two similar triangles with a common apex at the focal point of the lens may be imagined (Fig. 2).

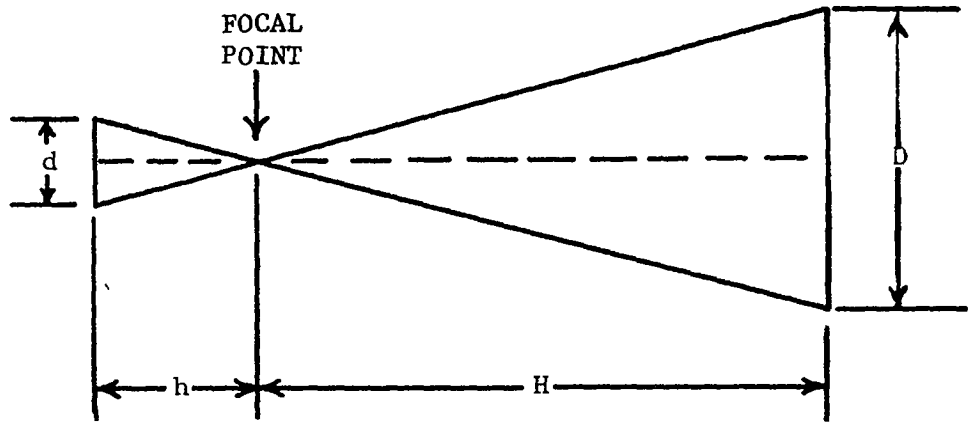


Fig. 2. Distance to a cloud point - "H"

In these two triangles, the values of "d", "h", and "D" are known:

d = the X-displacement of the cloud point between the two frames of the stereo pair.

h = the focal length of the camera lens multipled by the enlargement factor of the print.

D - the real displacement of the cloud point between frames; i.e., true air speed multiplied by the total elapsed time between the two frames.

The distance to the cloud point, "H", is then computed using ratio and proportion: h to d equals H to D.

b) The displacement of the cloud point from the center of the view field on the first frame of the stereo pair was computed by first determining its X-displacement on the photograph from the photo center. Again, similar triangles with a common apex at the camera focal point were formed, and the real displacement of the cloud point from the view field center was determined by ratio and proportion, the distance to the cloud point now being known.

c) The scale factor at the cloud point, expressed in units of mm kft^{-1}, was computed by dividing the X-displacement of the cloud point in millimeters between frames, by the real displacement in thousands of feet during the same time period. A mm km^{-1} scale factor was also computed by multiplying the mm kft^{-1} scale factor by kft km^{-1}. This latter scale factor was valuable in other calculations, such as computing cloud volume.

d) The height of a particular cloud point above sea level could be computed by multiplying its displacement, plus or minus, from the horizon on the first frame of the stereo pair by 1000, dividing this by the mm kft^{-1} scale factor, and then adding the altitude of the aircraft to the result.

2.1.3 Basic Assumptions in the Original Method.

Since the program used absolute values of X differences between frames, it worked equally well for both left-facing and right-facing cameras. It assumed that all cloud point displacements between frames were due to aircraft motion only, the aircraft and target cloud being in the same wind field. It was further assumed that displacement due to cloud-associated circulation between the first and last frames of the stereo series could be considered insignificant. It also assumed the horizontal plane in which the photo was taken to be flat. Therefore, declination of cloud features due to distance at aircraft altitude became insignificant.

This procedure, however, relied heavily upon an assumption of straight and level flight during the photo run. Based upon this assumption, the zero-yaw pair and aircraft horizon for each photograph were determined by means of an intricate graphic smoothing process and were checked against a visible horizon camera calibration run.

2.2 Areas for Improvement.

After several field applications of this method, two major areas needing improvement became evident. These were data turn-around times and reliability, both centering around the graphic analysis aspects of the procedure (par. 2.1, b & c).

2.2.1 Data Turn-Around.

Under the best conditions, approximately two man-hours were required to graphically extract all the data from one stereo set necessary for computerized analysis of particular cloud features. Considering the average daily stereo mission produced from four to eight stereo sets, as many as 16 man-hours were required just for manual data extraction for a single days mission output.

2.2.2 Reliability.

Any time a graphic process is employed for data extraction, especially one that is based upon assumptions of conditions that may not prevail during actual flight, and particularly one that utilizes graphic smoothing techniques, relative errors are introduced which are compounded as one stretches the validity of the basic assumptions. When the stereo aircraft maintains a reasonably level attitude during a photo run, the analysis procedure is quite reliable. Maximum apparent errors in cloud heights are on the order of ±1000 feet at a distance of 10 nautical miles from the aircraft. This compares well with other stereophotogrammetric techniques now in use. Occasionally however, straight and level flight attitude is not possible due to turbulence and cross-winds. Under these conditions, the graphic process could not be relied upon to produce accurate data.

2.3 Modification of the Procedure.

In partial fulfillment of the requirements of Contract No. F19628-

69-C-0239, AFCRL, the original procedure has been modified, eliminating a major portion of the graphics, the necessity for straight and level flight attitude, and the necessity for the visible horizon camera calibration run. These improvements were made possible by the installation of digital recording equipment in the stereo aircraft to store on magnetic tape all flight parameters necessary for the computer to indicate a zero-roll-yaw pair for each stereo series and then to compute individually a zero-roll-yaw point and horizon coordinates for the left and right margins of the zero-roll-yaw pair.

3.0 THE DIGITIZED APPROACH

3.1 The Airborne Stereo Data Package.

3.1.1 The Recorder.

The MSI Model DL620A Magnetic Tape Recorder has 20 data recording channels. It will scan and record data from all input channels according to the scane mode selected.

a) Continuous mode: One scan every 0.4 seconds continuously.

b) Ten-second mode: four continuous scans together at 10 second intervals.

c) One-minute mode: four continuous scans together at one minute intervals.

3.1.2 The Intervalometer.

The MSI Model SI-2 Stereo Intervalometer controls the selection of the stereo camera and its firing interval. The intervalometer has the following controls:

a) Camera Selection Switch: This three-position switch selects LEFT STEREO CAMERA, BOTH STEREO CAMERAS, or RIGHT STEREO CAMERA.

b) Mode Override Switch: This three-position switch selects the DL620A scan mode to be used during the stereo run.

c) ON-OFF Switch: This switch, used to start a stereo run, puts the DL620A into the scan mode selected with the Mode Override Switch and activates the Scan Counter.

d) Scan Counter: This device activates the camera firing mechanism and allows the position of the Camera Selection Switch to be recorded by the DL620A on each scan that the camera is fired. The Scan Counter has three selection positions which will fire the camera at intervals of four, ten or twelve scans. In combination with the Mode Override Switch, this allows four different firing intervals (Table 2).

Table 2. Camera Firing Intervals

DL620A MODE	SCAN COUNTER	FIRING INTERVAL
Cont	10	4 sec
10-sec	4	10 sec
10-sec	12	30 sec
1-min	4	60 sec

3.1.3 The Stereo Cameras

This system employs two Model F250 Motor Drive Nikon F cameras, designated LEFT STEREO CAMERA and RIGHT STEREO CAMERA, each utilizing with R60 and L39 Nikkor filters, a 35mm F:2 Nikkor-O Auto lens with the following specifications:

a) Focal length: 36mm

b) Horizontal viewing angle: 55 deg

c) Vertical viewing angle: 37 deg

3.1.4 The Camera Mount.

The MSI Model KL-3C Airborne Stereo Camera Mount is fully adjustable for roll, pitch and yaw. Span adjustment allows the camera mount to be fitted into all light single and twin engine aircraft. The main feature of this mount is that the optical axes of the two cameras remain colinear throughout all adjustment procedures.

3.1.5 In-Flight Data Sources.

a) An MSI-modified gyro-compass provides a compass heading to the nearest 0.1 deg. with no precession.

b) A Summers Gyroscope Co. Model 69 Vertical Gyro provides roll and pitch angle readouts to the nearest 0.1 deg.

c) An MSI Model TVH 26C measures outside air temperature, indicated air speed, flight altitude, and relative humidity.

d) An AIM Model 800 senses Variable High Frequency Omni-Range and Distance Measuring Equipment (VOR-DME) signals for recording.

3.2 Alignment and Calibration.

In order for this system to produce consistent and accurate data, a rather meticulous procedure for instrument calibration and camera alignment is necessary. The aircraft to be used for the stereo function should be chosen well in advance of any project, and the stereo function should remain with this aircraft throughout the project. Periodic calibration and alignment checks are essential.

The stereo cameras should be aligned and leveled with the aircraft at zero-roll and zero-pitch and with the common optical axis of the lenses perpendicular to the vertical plane through the longitudinal axis of the aircraft. In this way, the measurements of aircraft attitude recorded on the DL620A for each frame will directly reflect the attitude of the camera for that frame, allowing the horizon calculations to be made directly by the computer for each individual photograph of the stereo series.

The aircraft must be put into a level, zero-roll and zero-pitch, attitude in order to establish zero settings for the vertical gyro, and a determination of the longitudinal axis must be made in order to properly align the gyro-compass. The former is accomplished by jacking the aircraft into level position on the hangar floor. A longitudinal axis is located with a taut string running aft from the center windshield strut, assumed to be centrally located, and positioned equidistant from the sides of the fuselage.

Once the gyros are aligned and calibrated, camera alignment can begin, the aircraft still being in a level attitude. The camera mounting apparatus is completely adjustable for roll, pitch, and yaw and is so designed to be adaptable to all light single and twin-engine aircraft. The mount also insures that the optical axes of the two cameras remain colinear throughout all adjustment procedures. Zero-roll and zero-pitch are established utilizing bubble levels. Since the peak of the prism viewfinder of the Nikon camera lies in the vertical plane through the optical axis of the lens, zero-yaw is established by aligning a string between the peaks of the two viewfinders perpendicular to the string already located in the longitudinal axial plane of the fuselage.

3.3 The Zero-Roll-Yaw Pair and Horizon Program.

3.3.1 The Data Output.

Utilizing flight data recorded by the DL620A, the computer program computes and prints out, for each photograph in a stereo series, values for altitude, true air speed, VORI, DMEI, VORII, camera heading, yaw, roll, the zero roll-yaw point, and the horizon coordinates for the left and right margins of the photos; i.e., the vertical displacement from the bottom of the print. Other information picked off the DL620A tape includes starting and ending times for each run, average compass headin- for the series, and the active camera identification (Table 3.)

Table 3. Computer print-out for selecting the zero-roll-yaw pair and horizon calculations.

STEREO PHOTO ANALYSIS SERIES 0000 MISSION 01 DATE 12/17/69
STEREO DATE PACKAGE CALIBRATION CONTRACT

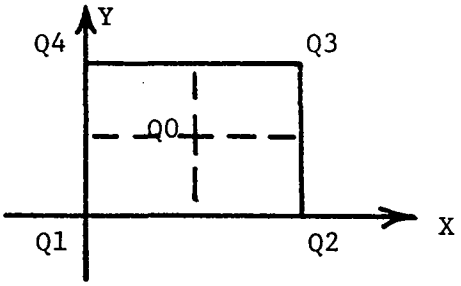
RUN 01 STARTING TIME 134523 CHAVG 203.1 LEFT STEREO CAMERA

NO	FLIGHT TRACK INFORMATION					CAMERA ATTITUDE			ZERO R-Y PT		HORIZON COORD	
	ALT (FT)	TAS (KT)	VORI (DEG)	DMEI (NM)	VORII (DEG)	HDNG (DEG)	YAW (DEG)	ROLL (DEG)	XZ (MM)	YZ (MM)	YL (MM)	YR (MM)
01	16500	168	327.4	57.7	178.4	113.2	+00.1	-00.5	110.4	078.6	068.7	085.4
02												
03												
04												
05												
06												
07												
08												
09												
10	16500	166	328.6	58.9	177.3	112.8	-00.3	-00.2	111.0	078.9	069.2	084.9

ENDING TIME 134603

3.3.2 The Coordinate System.

The coordinate references used for the computer program are shown in Fig. 3. The coordinate system is based upon a 6X enlargement of a 35mm negative. Units are millimeters.



Q0: (107.823, 072.009) - Frame Center
Q1: (000.000, 000.000)
Q2: (215.646, 000.000)
Q3: (215.646, 144.018)
Q4: (000.000, 144.018)
} Frame Corners

Fig. 3. The Coordinate System

3.3.3 The Sign Conventions.

It is necessary that sign conventions be established (Table 4) as signs for roll and pitch are reversed for left and right cameras. Yaw correction is independent of the camera used.

Table 4. The Sign Conventions for Various Aircraft Attitudes.

	SIGN OF INDICATED ATTITUDE ANGLE	
	POSITIVE	NEGATIVE
Attitude for indicated PITCH angle	Nose UP	Nose DOWN
Sign of PITCH correction-RIGHT CAM	+	-
Sign of PITCH correction-LEFT CAM	-	+
Attitude for indicated ROLL angle	Rt Wing UP	Rt Wing DOWN
Sign of ROLL correction-RIGHT CAM	-	+
Sign of ROLL correction-LEFT CAM	+	-
Attitude for indicated YAW angle	Nose RIGHT	Nose LEFT
Sign of YAW correction-RIGHT CAM	-	+
Sign of YAW correction-LEFT CAM	-	+

3.3.4 The Program.

a) The average compass heading is simply the arithemetric average of the compass headings of all stereo frames in the series. This produces a smoothed average course heading for the run and is used later to compute yaw.

b) Camera identification is necessary as indicated in the discussion of sign conventions (par 3.3.3). The phenomenon of reversed signs can easily be visualized by construction of a simple model.

c) Flight track information is computed using data supplied by the TVH 26C and the AIM 800. The program extracts and prints out VOR-DME indications and altitude, and then using indicated air speed, outside air temperature, and aircraft altitude, computes and prints out the true air speed.

d) The camera heading is the compass heading for the particular frame minus 90 deg for LEFT CAMERA or plus 90 deg for RIGHT CAMERA.

e) Yaw is determined by subtracting the computed average compass heading for the series from the indicated compass heading for the individual frame. A positive result indicates nose right; a negative result nose left.

f) The roll angle is simply extracted from the data tape and printed with proper sign.

g) The zero roll-yaw point is that point on the photograph where the optical axis would intersect if the aircraft had been flying at a zero roll and zero yaw attitude at the time the photo was taken. Thus determination of the zero roll-yaw point, XZ and YZ, requires corrections for roll, up and down rotation of the optical axis, and for yaw, left and right rotation of the optical axis. Since these rotations occur in planes perpendicular to the plane of the photograph, the mm deg^{-1} scale factor for the lens must be used to convert the angular displacement of the optical axis due to roll and yaw to a linear displacement in the plane of the print. Every lens, based upon its horizontal and vertical viewing angles, focal length, and the dimensions of the film negative used, has such a scale factor. This scale factor is constant for the entire field of view, since the field of view is the distortion-free central segment of the total cone of vision of the lens. The WSI Stereo Analysis Method employs 6X enlargement photographs from 35mm negatives, so the scale factor based upon this print size and the specifications of the Nikkor-O Auto lens is 3.9066 mm deg^{-1}. The equations used to compute the zero roll-yaw point retain the sign of the indicated roll and yaw angles, and for roll are dependent upon the camera used. Values are for the coordinate system shown in Fig. 3, with results being rounded to the nearest 0.1 mm.

1) X-Coordinate is yaw dependent and camera independent.

$$XZ = [(107.823) - (3.9066 * \text{YAW ANGLE})]$$

2) Y-Coordinate is roll dependent and camera dependent.

RIGHT CAMERA

$$YZ = [(072.009) - (3.9066 * \text{ROLL ANGLE})]$$

LEFT CAMERA

$$YZ = [(072.009) + (3.9066 * \text{ROLL ANGLE})]$$

h) The aircraft horizon pivots around the zero roll-yaw point and is direct function of the aircraft pitch angle, having equal magnitude and opposite sign. By knowing the coordinates of the zero roll-yaw point and the indicated pitch angle in degrees, the Y-values for the intersections of the horizon with the left and right margins of the photograph, YL and YR, are computed. The equations used retain the sign of the indicated pitch angle and are dependent upon the camera used. Values are for the coordinate system shown in Fig. 3, with results being rounded to the nearest 0.1 mm.

1) RIGHT CAMERA

$$YL \text{ (left margin)} = \left[(YZ) - (XZ * \tan PITCH)\right]$$

$$YR \text{ (right margin)} = \left\{(YZ) + \left[(XR - XZ) * \tan PITCH\right]\right\}$$

where XR = 215.6

2) LEFT CAMERA

$$YL \text{ (left margin)} = \left[(YZ) + (XZ * \tan PITCH)\right]$$

$$YR \text{ (right margin)} = \left\{(YZ) - \left[(XR - XZ) * \tan PITCH\right]\right\}$$

where XR = 215.6

3.4 Selecting the Zero-Roll-Yaw Pair.

Once these computations are printed out, the analyst must select the zero-roll-yaw pair. Practically speaking, any two frames of the stereo series could be selected for cloud point analysis (par 2.1), since the horizons for each frame have been corrected for roll, pitch, and yaw. However, it is desirable that the pair be a zero-roll-yaw pair in order to present a distortion-free optical model of the target cloud when viewed through a stereoscope.

First, a zero-yaw pair is selected utilizing the printed yaw data for each frame. It is of primary importance that the zero-yaw pair be as close to "absolute" zero-yaw, with respect to the flight track, as possible. This will keep any errors due to a skewed baseline at an insignificant level of magnitude (Haller, 1960). It is also desirable, though not totally necessary, to have the zero-yaw pair separated by several frames so that movement of distant cloud points between frames can be more easily and accurately detected.

Next, the roll data for the selected zero-yaw pair is examined. If the roll angles are equal, this pair becomes the zero-roll-yaw pair. If the roll angles are not equal, the selection of the zero-roll-yaw pair becomes a matter of equalitative judgement by the analyst, with the primary consideration being "absolute" zero-yaw with respect to the flight track.

When the zero-roll-yaw pair has been selected, the computed horizon is plotted on each of the two frames; and cloud points of interest, identifiable on both frames, are selected. The cloud points are given location identification on the analog digitizer, and the computer program described in par. 2.1.2 is then run. Data output is as shown in Table 1.

1.

3.5 Mosaics.

The program is also designed to compute data when both stereo cameras

are operating simultaneously. Such a situation may arise when the photo aircraft flies between two target clouds. More often, however, a mosaic is desired depicting an overall sky condition, as in convective band analysis. The horizon data is then used in constructing the mosaic. The longer, 30 second and one minute, camera firing intervals are desirable for mosaic work.

4.0 ERROR ANALYSIS

4.1 Geographical Location of the Target Cloud.

VOR-DME signals do not have the precision necessary to pinpoint the location of the aircraft. The Variable High Frequency Omni-Range (VOR) system is subject to a number of inaccuracies, some of which cannot be corrected by instrument calibration. The VOR station transmits two signals, one radiating and one rotating beam. The location of the aircraft is determined by measuring the phase relationship between these two signals.

Transmission errors are usually constant for a particular VOR station, but vary from station to station. The phase of the rotating beam signal varies with rotation. This is a mechanical problem. Path distortion occurs due to reflections from ground obstructions. The beam width varies with distance from the transmitting station introducing a possible angular error when determining the beam center.

The limiting factor, however, in absolute accuracy is one of resolution. The signal transmitted is a 9960 HZ signal modulated by a 30 cps sine wave signal. The finest resolution attainable from this signal configuration is 1 deg.

Errors in the aircraft receiver can be determined by calibration and are mainly the result of phase shifts in the electronics of the receiver system. However, errors due to variations in signal strength are not always definable. One signal is amplitude modulated, and the other is frequency modulated. The AM signal is affected by the signal strength, and apparent phase variations will appear with weak signals.

The maximum transmission error is about 1 deg. The maximum receiver error is about 2 deg. Even under ideal conditions about 1 deg. of undefineable error is present in the VOR system. At 50 nautical miles from a VOR station, this represents a deviation of 0.9 nautical miles from a true fix.

The Distance Measuring Equipment (DME) is considerably less complicated and more precise than the VOR system. The aircraft transmits a pulsed signal which is retransmitted exactly on a different frequency by the ground station. The time between pulses transmitted and received by the aircraft indicates the slant range from the ground station.

The accuracy of the DME depends upon the calibration of the aircraft

DME equipment with 0.1 mile accuracy possible. The maximum allowable error is 1 mile with the average being about 0.5 miles.

Thus the test cloud cannot be located with certainty when VOR-DME is the only available aircraft tracking device. In many field situations, there are other methods of locating the test case that do not depend upon the stereophotographs. One such method is radar tracking of the penetration aircraft. However, when the stereo aircraft is operating alone, it must be tracked by radar if precise location of the test case is an important factor.

4.2 Experimental Error.

As indicated by Herrera-Cantilo (1969), the determination of experimental error in aerial photogrammetry brings up the question of the accuracy of aircraft instrumentation and of airborne meteorological sensors. Conclusive results from experiments in these areas have not as yet been published. Therefore, the maximum relative error can only be estimated using the manufacturer's quoted specifications (Table 5). Based upon these figures, the maximum apparent error in vertical and horizontal dimensions at ten nautical miles from the aircraft is ±1650 feet; at twenty nautical miles, ±3300 feet. After experimentation, Herrera-Cantilo computed a maximum apparent error in vertical dimensions of around ±750 feet.

4.3 Data Confidence Level.

A calibration check for the entire data package has been designed. By flying stereophoto passes a measureable distance from a landmark of known height, the stereo data output can be checked with precision. Pre-flight instrument calibration and post-flight calibration checks will indicate instrument variances for which spot corrections can be made.

Variations in flight attitude, altitude, and distance to target during testing will indicate the performance capabilities of the system. Several test days will allow an initial confidence level for the stereo data to be established.

Table 5. Manufacturer's specifications for the airborne stereo data package.

DATA	SENSOR	RANGE	ACCURACY	RESOLUTION
MSI Model DL620A				
Recorder	1/4 inch digital magnetic tape recorder	0-5 VDC input	0.05% FS	-
Time	Crystal controlled digital clock	0-24 hrs	2 sec/day	1 sec
MSI-Modified Gyro Compass				
Compass heading	Gyro-stabilized flux gate compass with shaft encoder output	0-360 deg	1 deg	0.1 deg
Summers Model 69 Vertical Gyro				
Roll & Pitch	Potentiometric inner and outer gimbal	±79 deg	1.5 deg	0.1 deg
MSI Model TVH 26C				
Temperature	Hewlett-Packard quartz thermometer	±40C	0.1 C	0.1 C
Humidity	Carbon strip hygrister element	40-90% RH	5% RH	0.4% RH
Altitude	Potentiometric altitude transducer	0-30 kft	70 ft	20 ft
Airspeed	Potentiometric indicated airspeed transducer	40-300 kts	2 kts	0.3 kts
AIM Model 800				
VOR radials	AIM Model 800 with digital shaft encoders	0-360 deg	2 deg	0.3 deg
Distance from VORTAC	Digital DME with digital output	0-100 nm	0.1 nm	0.1 nm

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DECISION MAKING IN A PRECIPITATION MANAGEMENT PROGRAM

By

Steven H. Cohen

OAWR Bureau of Reclamation - Denver, Colorado

To adequately discuss decision-making as it applies to our field, we must examine, first of all, the present meteorological information system and, secondly, a systematic breakdown of the weather modification problem. The questions we are ultimately trying to answer are:

1. How can the meteorological information structure be reordered to maximize effectiveness for both the meteorologist and user?

2. What are the needs and priorities in a weather modification decision system?

It is probably more adviseable to first examine the present meteorological system and its attendant difficulties which is an area that affects many user-oriented problems of today, such as air pollution, urban traffic congestion, air traffic control, and, of course, weather modification. An essential element in each of these is the ability to understand and predict the atmospheric environment and to subsequently integrate environmental information into operations and planning. The current meteorological system was never designed to meet this need. An apparent answer to expanding complexity has been to increase the amount of information dispersed.

Today the meteorologist and user alike are faced with mountains of data transmitted in a less than optimum manner employing archaic coding systems. How can the meteorological information structure be reordered to maximize effectiveness for both the meteorologist and user? The most likely solution is a system providing for a greater flexibility and increasing the options for which the information can be used. In this way, the meteorologist benefits by having a more flexible basis for meteorological decision-making, and the user has access to vital information which can be intergrated into his decision-making process.

The major means of data interchange, at the present time, are teletype and facsimile. The facsimile output, prepared by the National Meteorological Center is in the form of two dimensional maps which are distributed over a nationwide network. The map formats include a variety of parameters presented simultaneously on horizontal displays. One problem is that the various horizontal "slices" are not consistent

in scale, making it difficult to integrate visually between levels.

Teletype is primarily used to present current weather conditions by means of several alpha-numeric codes, although forecasts are transmitted on both national and regional levels. Historically, the weather teletype circuits evolved in proportion to the growth and geographic distribution of our population in the past 60 years. Some attempt was made in the very early stages of development to optimize the networks by ordering stations according to their positions relative to one another. However, this attitude was abandoned in favor of a more expedient approach: When an urban area grew to a large enough size, commercially, to warrant the needs of a first-order weather station, its communications were "tacked" on the end of the circuit. Consequently, the networks represent, for a meterologist's purpose, what approaches a random station order.

The present information structure is based upon a national meteorological center, regional centers, and individual stations. NMC is responsible for worldwide data collection, distribution, and analysis and prognosis transmitted over the national facsimile and teletype networks. The regional centers are responsible for area forecasts and aviation forecasts for airways within their area of responsibility. The regional offices have some degree of flexibility in coordination of their forecasts with NMC analysis and prognosis. The individual stations generally act as the direct interface between the users and the analysis-prognosis products. However, the stations are hampered by the need to generalize in order to serve as broad a user spectrum as possible and the requirement to closely coordinate forecasts with the regional center and NMC products. The mechanism for feedback from the stations to the regional centers is minimized, and, consequently, the stage at which the greatest flexibility and interchange should occur is the opposite in practice.

A typical first-order station may consist of as many as three forecasters on duty at any one shift. The area of responsibility of each forecaster is supposedly separate. These areas are designated by such titles as chief forecaster, aviation forecaster, public forecaster, etc. Often all of these areas are handled by a single man. Although supposedly separate, these areas utilize the same forecast wording with only slightly different emphasis. So a great deal of redundancy occurs because the product must remain general in nature.

The technological advances in the past 30 years have created an urgent need for specific meteorological information in many areas of interest, as was mentioned earlier. The meterological organization, on the other hand, has grown from an agricultural service where user orientation was an almost irrelevant issue to the present complex system in the same relatively short period. Thus, it is not difficult to understand why specific user needs present such a large challenge and burden to the present information system.

There have been some advances - for example, a more adequate

service for the aviation field which had an earlier and more direct specific user need has been developed. The military meteorological organizations have felt the demands of increased technological capabilities and have taken some beginning steps in meeting these requirements. The Navy has adopted the concept of analysis of the "total environment" from the top of the atmosphere to the sea floor and has developed special antisubmarine warfare environmental prediction teams to meet operational needs.

What is needed, then, is a cybernetic approach which enables the meteorologist to view many parameters and combination of parameters and to utilize numerical and empirical models in an effort to "quicken" changes in atmospheric conditions.

The meteorologist can thus impose many alternatives or constraints upon his environment so that he can effectively evaluate the present and probably future states of the atmosphere. This is not to say that the present products are ineffective. The important issue is that in order for the developed models and simulations of the environment to be pertinent, they must be incorporated into a man-machine mix. Having described the problems of the present meteorlogical information system, the next question we must examine concerns the needs and priorities in a weather modification decision system. For discussion purposes we will assume an emphasis upon precipitation management. The precipitation management problem can be divided into four general components or categories: Analysis, opportunity recognition, treatment, and evaluation. The first component, analysis, specified the nature of the water need, examines the potential sources, and estimates associated economic, hydrologic, social and legal effects. The second component, opportunity recognition, provides the decision of treatability. Pertinent cloud characteristics are examined, such as temperature structure, moisture profile, stage of development, and drop-size spectrum. Other features such as air-mass characteristics and significant terrain influences are identified and described.

When the decision is made that a storm is treatable, the system leads to the treater function. The characteristics of all treatment agents are evaluated (activation temperature, decay rate, etc.). When the best treatment agent for the particular storm at hand is determined, the appropriate delivery system is selected. The optimum agent size and concentration are specified, and the duration of treatment is decided upon.

The final component in the system is the dual purpose evaluator. This component continuously monitors each of the other functions and verifies that the water need still exists and that safety limits are not being approached. It also gathers data and analyzes the results of the treater function to assess the success of the operation. Ideally, the evaluator is operating near real-time giving at least probabilistic results suitable for real-time decisions about continuing or terminating the treatment of individual storms.

What becomes obvious from the definitions is the fact that we are faced with decisions that must be made on varying time and geographic scales. Decisions which involve national and regional scales, long-term economic, ecological, socialogical and legal problems - problems of coordination and cooperation between groups which vary widely in nature. There is also the command and control problems associated with individual field sites. These problems have a smaller critical time factor and involve decisions that have to be made in terms of minutes and hours versus days and weeks. What we are talking about, then, is a systems development that will meet the decision requirements of the precipitation management user and overcome the constraints of present information processes. This development must emphasize short-range advances such as the screening and selection from available sources, methods and criteria that can best satisfy analyses requirements without exceeding existing processing capabilities. Secondly, long range objectives such as testing and implementation of system designs and data processing and display techniques must be defined and programmed for development. Some technological capabilities which can be integrated into first approach systems have recently been developed and are being tested and applied within existing field programs. Two specific examples - and please bear in mind that we are only offering examples and not an exhaustive list of up-to-date developments - are a real-time airborne radar display system developed by the Desert Research Institute, University of Nevada, which generates and displays very precise contours and the expansion and/or contraction of the enclosed area with an increase or decrease of cell activity.

The second example is a sounding analyses procedure developed by the Denver Research Institute, University of Denver, which utilizes mandatory and significant level radiosonde data as input and presents a real-time output display of a number of thermodynamic parameters for any given height increment. This program is being expanded to include service C radiosonde data as directed input and will permit desired plotted cross sections as output.

During February of this year, the Bureau of Reclamation's Office of Atmospheric Water Resources is conducting an experiment designed to explore the development of general meteorological/user interface requirements. This experiment is a first effort to coordinate precipitation management activities on a synoptic scale.

Several field locations and the Desert Research Institute's B-26 are being coordinated from the Bureau of Reclamation's Office of Atmospheric Water Resources at Denver. A key aspect of this experiment is a linkup between sites to the GE-time-share computer system which allows a means of rapid data exchange of raw and analyzed data and a great deal of flexibility in decision making at the field sites and the Office of Atmospheric Water Resources. It is possible, for example, for the Office of Atmospheric Water Resources to place radiosonde information available from the Western States in the system, and each group can obtain cross section information as desired by that group, In addition, every other

group has access to the latest information such as radiosonde data, operations summary, etc., of any individual group. The time-share system also allows the users to anticipate changes in conditions such as cold air advection and analyze their data accordingly by altering data input.

As a final example of the sort of processes we have been discussing let me offer one possible alternative for an eventual, coordinated, national system. My objective here is to further illustrate the various scales and types of decisions made rather than the type of organizational structure used. In this example, there are three basic units - a national center, regional centers, and field groups. The national center would receive synoptic scale data (satellite, standard upper air, and surface data, etc.) on a routine basis.

The national center would also have as background economic and hydrologic data available for broad-scale decisions involving possibilities for seeding on the regional scale and beyond. Assuming a favorable situation were developing on a synoptic scale (a low in the Gulf of Alaska moving onshore) the national center would make a tentative go, no-go decision and commence coordination activities with the appropriate regional centers and field groups who would start to take special soundings and make aircraft probes and radar observations as needed for opportunity recognition.

Based upon synoptic information from the national center and detailed information such as cloud characteristics and local kinematic fields and nonmeteorological data such as the individual field units user requirements (water districts, etc.), the regional centers would make a go, no-go decision. The regional center, if it is a go, would then coordinate seeding activities with the field units within each region. The field units, upon receiving a regional go and making their own seeding decision, would commence seeding command and control functions which include real-time evaluation of radar, airborne and ground telemetry, and special surface and upper air observations.

Once seeding operations commence, a continuous monitoring function is established by the regional centers who evaluate data from the field units and pass processed information to the national center for further evaluation. During seeding operations the national center is also responsible for liaison between regions.

The general goals to be working towards, then, are to:

1. Maximize options at all levels from the national center to the field units.

2. Provide information exchange between all levels and scales.

3. Create an environment conducive to user needs nationally, regionally and locally.

To quote Richard W. Hamming, Director, Computing Science Research Department, Bell Laboratories:

> "I have a warm spot in my heart for machines and I resent the misuses that give computers such a bad name. In the long run, if we are going to end up with a liveable society, we are going to have to insist that those who program computers understand their social responsibility and use some of the machine's capacity to create a society with a large amount of human freedom."

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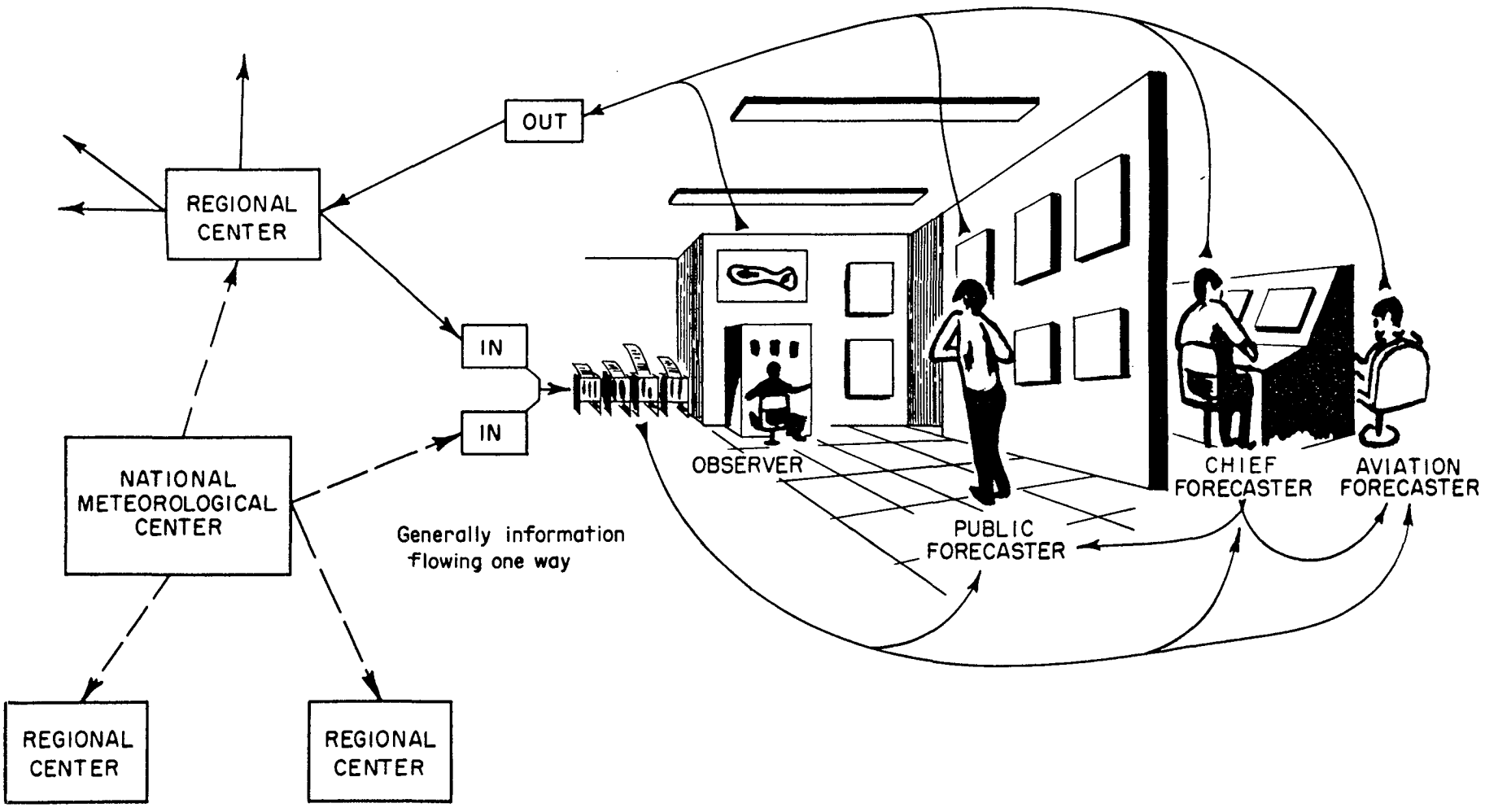
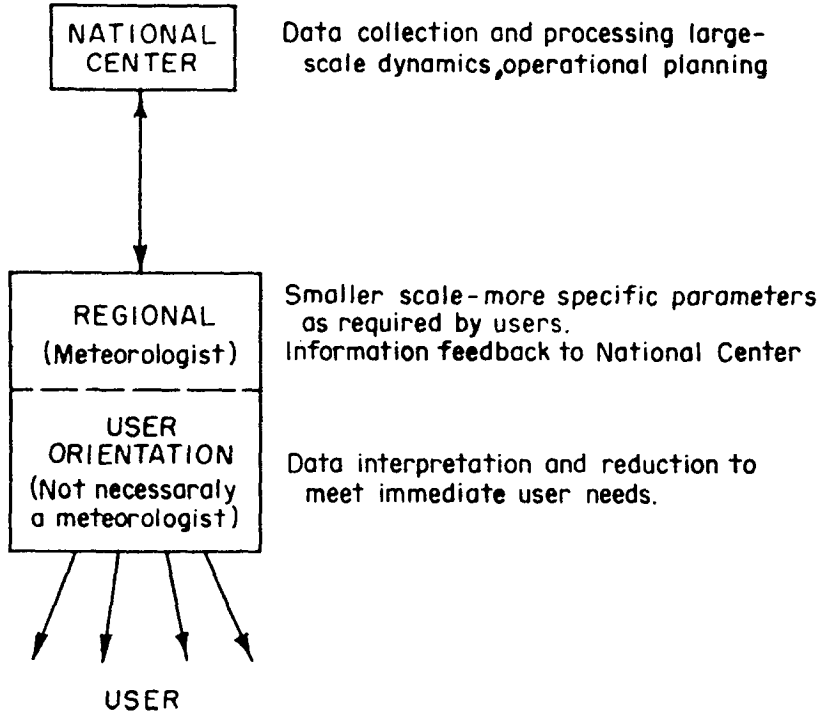


PRESENT METEOROLOGICAL INFORMATION SYSTEM


NATIONAL CENTER
Data collection and processing large-scale dynamics, operational planning
REGIONAL (Meteorologist)
Smaller scale-more specific parameters as required by users.
Information feedback to National Center
USER ORIENTATION (Not necessaraly a meteorologist)
Data interpretation and reduction to meet immediate user needs.
USER

PROPOSED INFORMATION SYSTEM

MEASUREMENT OF ATTITUDES TOWARD WEATHER MODIFICATION

Darlene A. Krueger

Fresno State College Foundation
Atmospheric Water Resources Research
Fresno, California

INTRODUCTION

It is the purpose of this study to attempt measurement of public attitudes toward weather modification. The necessity of such a study is evident in that there is at present no extensive, reliable data about the nature, distribution and intensity of public approval or disapproval, the state of the public's knowledge of present or potential weather modification, its concept of appropriate regulation and control, financial responsibility and professional qualification. Measurement of such was accomplished by way of a written questionnaire during the summer of 1969. The study was funded by the Office of Atmospheric Water Resources, U.S. Bureau of Reclamation, Contract No. 14-06-D-6592.

The geographical area measured was Fresno County in the San Joaquin Valley of California. The appropriateness of this area for measurement is related to its dependence on runoff waters from the Sierra Nevada for irrigation of extensive agricultural areas. As the San Joaquin Valley is considered a veritable desert, weather modification is seen as a potential aid to the agricultural economy in what might otherwise by a dry growing season. In addition, a certain amount of operational and research activity directed toward increasing rainfall in the area has been conducted in varying degrees for the past twenty years (1), (2), (3).

This paper represents the results of that attitude survey and attempts to identify subgroups holding to certain beliefs and patterns of attitudes.

DEVELOPMENT OF INSTRUMENT AND SAMPLING TECHNIQUE

A. The Questionnaire

Library research on the subject of weather modification led to the selection of a number of potential areas of investigation. These included attitudes (such as legal questions, ideal weather, financial obligation, etc.) and extent of knowledge the general public possessed relative to weather modification activities. In order to assess social determinants of these attitudes, personal interest areas were a main concern. These potential areas were integrated into a written questionnaire (Appendix A) which was validated in a short pilot study and distributed by mail to a selected sample of subjects.

B. Sampling Technique

A random sample of five percent of the voters in Fresno County was obtained utilizing voter registration rolls. At that time, the occupational status of each subject was noted and classified for later use.

In an effort to increase mailed returns beyond the expected ten percent, a news release describing the proposed project was prepared and sent to every newspaper in Fresno County. This was done four days prior to mailing the questionnaire.

RESULTS

Of the 7,086 questionnaires mailed out, 1,420 were returned and utilized for analysis. This represents 20 percent of the original sample and thus, 1 percent of the voters of Fresno County.

In an effort to assess the representative quality of the sample to the population, some correlative statistics were employed. Pearson product moment correlations (4) comparing occupational status of Fresno County to that of recipients of mailed questionnaires (selected sample) to that of the group actually returning the questionnaire (effective sample) are as follows:

	Census	Selected Sample	Effective Sample
Census	1.0000	.9840	.9897
SS		1.0000	.9695
ES			1.0000

Geographical representation was determined by tallying postmarks on returned questionnaires. The correlation of postmarks by cities to actual census of these cities was .9565. A final measure of the representative nature of the sample correlated political party affiliation of the effective sample with that of the entire population of voters in Fresno County. A correlation of .9479 was obtained.

From the near-perfect, positive correlations obtained, it can be inferred that the sample population is representative of the actual population of Fresno County, at least in terms of occupation, geographical distribution and political affiliation. With these relationships established, it would seem justifiable to generalize any results obtained to the entire population of Fresno County.

A computer program for tallying responses for all questions was utilized. The following tallies were made: All questionnaires; tallies by residence (2 categories); by occupation (7); by educational background (6); by main areas of study (8); by religious affiliation (7); by political affiliation (4); by importance of religion (3); by importance of conservation (3); and by degree of approval (6).

In considering the overall responses of all questionnaires, a slight majority reported awareness of local activities. Close average estimates relative to length of weather modification activities in the area, effect of weather modification on the water supply in the Sierra Nevada, and effect of chemicals on wild life were registered, indicating fairly accurate knowledge. These estimates allowed for exclusion of respondents who felt they did not have sufficient knowledge to answer the questions.

In general, respondents indicated neutral to slight approval of weather modification. In rating the seriousness of related issues, the following were indicated in order of most to least serious: Development of appropriate laws to deal with related problems; financing of weather modification; government regulation of activities; pollution caused by chemicals used in modification activities; weather modification as a potential military weapon; problems involving international politics, and moral issues. As can be seen, the more seriously rated items appear to be those in which fewer persons are likely to possess knowledge of the implications.

In rating the importance of certain aspects of their personal lives on a most to least scale, respondents answered as follows: Conservation, outdoor sports, travel, religion and politics.

As the previous rating indicates highest importance to those aspects closely related, if not dependent, on weather, the sample of population should potentially be motivated to show a fair degree of interest in the subject of weather modification, and thus, the questionnaire they received.

In considering differences between urban and rural residents, it can be said that rural residents are more dependent on weather for income, more aware of the weather modification activities in the area and their length of occurrence, and are less inclined to rate potential problem areas as serious. On the other hand, urban residents indicate more dependence on weather for leisure, have a higher average measure of approval of weather modification, and record less "no knowledge" responses on questions of potential problem areas.

The results relative to occupational differences indicate that agriculture and construction are more dependent on weather for income, more aware of the local activities and more in favor of weather modification when compared to the other occupational categories of unemployed, manufacturing transportation, wholesale-retail trade and miscellaneous.

The relationships afforded by increasing levels of education can be restated to indicate increasing awareness of local activities, increasing approval, slightly decreasing estimation of seriousness of potential problem areas, and decreasing "no knowledge" responses to potential problem area questions.

The results according to areas of study give some support for the generalizations that awareness of modification and approval seem to relate

to higher knowledge of related issues and a feeling that these issues are less serious than others indicate. Agriculture, science or math, and social science majors were generally most aware and most approving.

In dealing with various religious affiliations, approval of weather modification appears to correspond with more knowledge of issues and less serious rating of those issues. High knowledge of modification activities in the area related to these other areas only with regard to Jewish respondents. Agnostics and Atheists know least of local activities, yet are included as highly approving, claiming knowledge of related issues, and rating those issues as not serious.

No identifiable patterns of responses are available according to various political affiliations. Perhaps this can be accounted for by the extreme heterogeneous mixture existing within each party.

By breaking respondents down into high, medium and low relative to importance of religion in their lives, it can be seen that the more important religion is to an individual, the less he is aware of local weather modification, the less he approves of weather modification, the more serious he feels related issues are, and the more "no knowledge" responses he indicates to questions of issues related to weather modification.

Results relative to high, medium and low classification on importance of conservation show that the importance of conservation corresponds to knowledge of local weather modification, approval of weather modification and knowledge of related issues. While high, medium and low conservationists rate the seriousness of these issues as most, middle and least, the differences are not significant. And, finally, high, medium and low on the conservation scale is the best ordinal predictor available for importance of religion, politics, outdoor sports, travel, and leisure to weather. It should be noted that the combined attributes of high importance of conservation and high importance of religion appear to have different attiudinal effects than high importance of religion alone. Where the combined effect is one of high approval, high importance of religion considered singly has an opposite effect.

From close examination of graphs of frequency distributions of attitudes, it was noted that an upturn of the curves at either extreme was a characteristic occurrence (Figure 1.). In order to determine the cause of this, tallies were run according to high and low approvers (where the 1 to 7 scale indicated high to low approval); i.e., those indicating 1, 2, 1 or 2, 6, 7, and 6 or 7 to question 27 regarding the amount of approval toward weather modification. Overall implications of that analysis indicated the following relationships: (a) the ability or tendency to form finer discrimination of attitudes (i.e., between extremes) is related to youth and length of schooling; (b) the higher educated and younger are more in favor of weather modification; (c) extreme 7 (low approval) ratings are related to firmness of religious convictions, while a lesser religious orientation permits finer discrimination; and (d) the high approving group reported more awareness to the fact that weather modification

was going on, as well as reporting more knowledge of its effects and the effects of chemicals used in the process.

DISCUSSION AND CONCLUSIONS

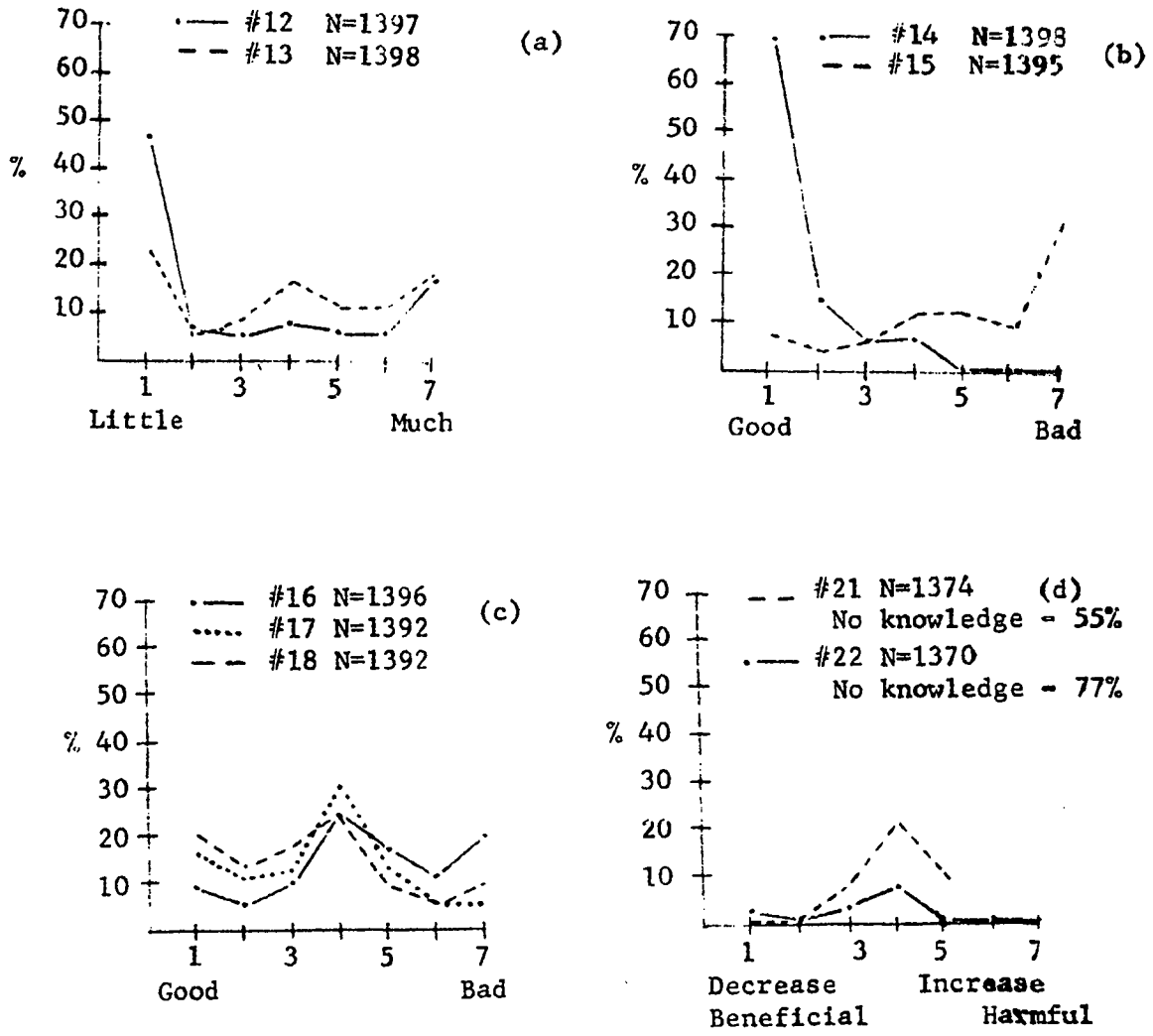
On the basis of the somewhat extensive results of this survey, some major determinants of attitudes toward weather modification -- both favorable and unfavorable -- can be suggested. Favorable attitudes appear to be based on one of several -- or combinations of several -- forces. One of these forces can be identified as financial dependence on weather. Agriculture and construction industries best demonstrate this relationship. The dependence of agriculture is most obvious in that controlled and predictable rainfall could serve to decrease losses associated with excessive dryness or unexpected storm loss. The motivation of construction interests is perhaps less apparent, as rainfall tends to slow down construction operations. As a possible explanation, perhaps construction interests realize the importance of weather modification to this particular agriculturally-based economy. Construction tends to flourish in time of economic prosperity.

Two further determinants of favorable attitudes that would seem to be somewhat related are education and technological knowledge. The statistical results clearly demonstrate the effect of higher education on increased favorability and knowledge concerning weather modification. While increased education presupposes a certain degree of increased technological skills and understanding, further support for the importance of this attitude is evident in the analysis by areas of study. Science or math majors appeared as the highest approving and one of the most knowledgeable and aware groups listed.

Importance of conservation appears as the most clear-cut determiant of favorable attitudes as demonstrated by statistical analysis. While high conservationists are the highest approving (relative to medium and low conservationists), they are also high in awareness, knowledge and all areas that would assume dependence on weather (e.g., weather for income and leisure, travel and outdoor sports).

A prime indicant of unfavorable attitudes toward weather modification (which, incidentally, derives directly from indicants of favorable attitudes) is low education. Just as the highly educated are highly aware, knowledgeable and favorable, those with lesser educational experience are less aware, knowledgeable and favorable. Unemployed individuals, which appear generally in the lower echelons of education, also follow this pattern.

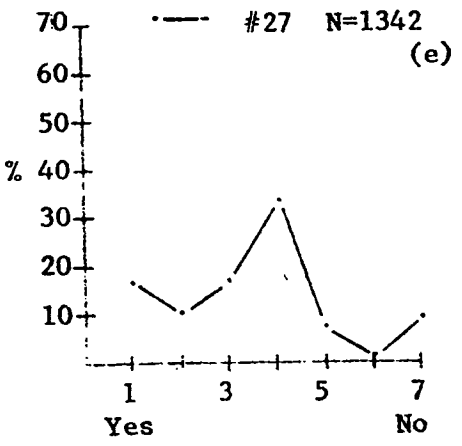
The major index of unfavorable attitudes is afforded by a high, medium or low classification relative to importance of religion in one's life. Generally, individuals with strong religious convictions are less in favor of weather modification, less aware, less knowledgeable and tend to rate potential problems as more serious than others do.

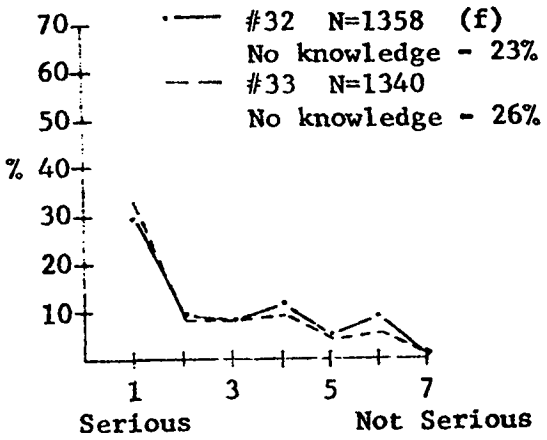


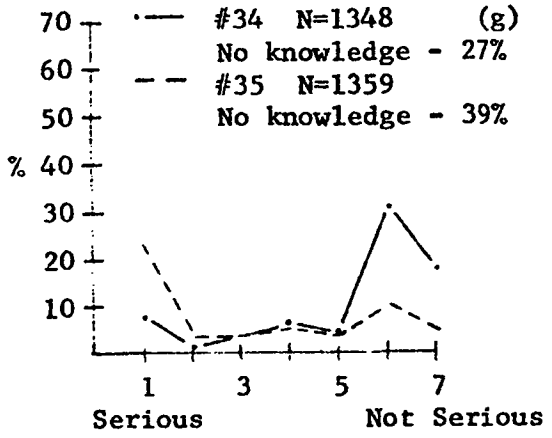
KEY:
Numbers (#) on each graph refer to question number on survey (Appendix A).
N=Total number of respondents to that question.
"No Knowledge" refers to total number of respondents who indicated "no knowledge" in answering the question.

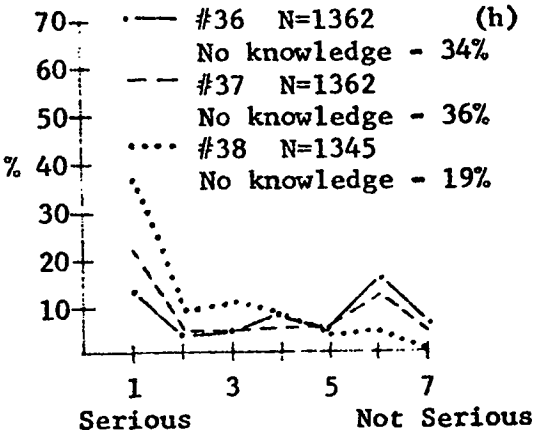
Graphs shown pertain to the following topics: Graph (a): importance of (#12) weather to income; (#13) weather to leisure. Graphs (b) and (c): how do you feel when it is (#14) sunny; (#15) foggy; (#16) windy; (#17) cloudy; (#18) rainy. Graph (d): effect of (#21) weather modification on the water supply; (#22) chemicals used in weather modification on plant and animal life. Graph (e): (#27) amount of approval of weather modification. Graphs (f), (g) and (h): rate of the seriousness of the following issues -- (#32) government regulation of weather modification activities; (#33) financing; (#34) moral issues; (#35) pollution caused by the chemicals used; (#36) international politics; (#37) potential military weapon; (#38) development of appropriate laws. Graphs (i) and (j): in your personal life rate the importance of -- (#39) religion; (#40) conservation; (#41) outdoor sports; (#42) travel; (#43) politics.

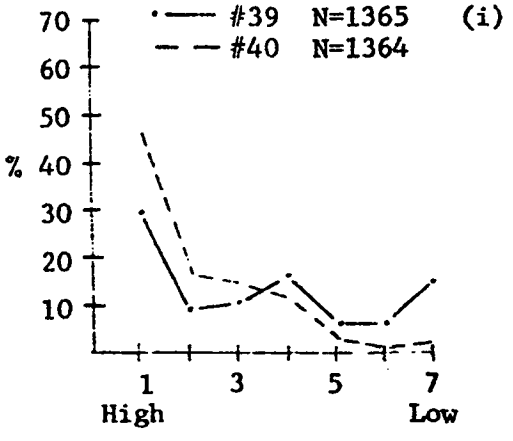
Figure 1.











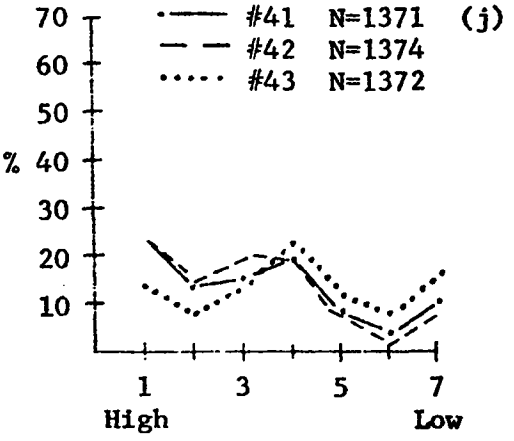


Figure 1. (Continued)

In an overview of all results sections, one common recurring tendency is for favorability of weather modification to coincide with claimed and demonstrated knowledge as well as indications that related issues are not so serious as others rate them. Overrating the seriousness of issues is probably due to common tendency to fear the unknown due to apparent mysterious qualities.

It perhaps goes without saying that the preceding statements are based on generalizations. Isolating determinants of attitudes is a most difficult task due to the unique qualities within each individual. One or more of the indicated characteristics may take priority in forming an individual's attitudes, or they may react in combination with other overriding or neutralizing agents. It should also be noted that the results of this survey are most likely unique to Fresno County. Given a replication of this survey in a less agriculturally-based economy, one would expect somewhat different levels of awareness and involvement in the topic of weather modification. Assuming that weather modification interests desire to further approval for their cause, the results of this survey may be used to suggest methods for creating an atmosphere of favorability.

Even though individuals cannot be made dependent on weather for their personal income, perhaps an inter-dependence can be established. For instance, increasing the farmer's yield and profit has a direct effect on grocery prices, thus affecting everyone in the society.

The most obvious possibility for increasing approval is a program of education relative to weather modification. Individuals could be given an historical perspective as well as the potential outlook for the future. Discussion of issues related to weather modification might serve to bring familiarity and awareness, and, hopefully, alleviate ungrounded fears. There is the added possibility that this process might strengthen existing negative attitudes. Such is the prerogative of the individual. At least he will have formed his opinions on a factual foundation.

The religiously-based negative attitude presents itself as the most difficult encounter. Since such attitudes often are not based on reason, but rather on emotion, any attempt to alter such opinions might typically be a waste of time. Various members of the local (Fresno) clergy have confirmed the uselessness of attempts to sway religiously-based viewpoints. At the same time, they have suggested that there is nothing in the realm of weather modification which contradicts the teachings of those particular religions in question.

The common approach to soliciting approval and funds for weather modification has heretofore involved contact with various organizations, service clubs, etcetera. While this has been a sufficient technique to this point, evidence from this survey suggests possible problems in the future. If approval of a large weather modification project should hinge on the vote of the entire county, noticeable opposition is likely to spring up. The mere fact that this opposition participated in the survey indicates

that they would not represent apathetic, non-voters.

The problem at hand is how to reach the less-consulted, less-approving, less knowledgeable economic minorities. It must be noted that this group includes but certainly does not exhaust ethnic minorities. It is also made up of a large number of the tradiationally labeled White Anglo Saxon Protestant element. How can this economic and educational minority be effectively contacted and presented with proper evidence leading to sound decisions? Assuming that a large number of the potential non-approving voters do not subscribe to local written news media, and in fact, do not possess basic reading skills, the possible effectiveness of the newspaper is eliminated.

As an alternative, a rather easily and quickly understood approach would be through development and distribution of animated explanations. Or, if attendance was assured, animated films might be shown at various gatherings, and, in fact, on television. In addition to reaching the older, less literate citizens, youngsters would be more likely to understand the potential importance of an issue so vital to their future. If other popular means of communication for this minority could be adequately identified, perhaps additional recommendations could be made in this area.

Recently, an upsurge in organizing powers of ethnic minority and minority-oriented groups has been noted. It is proposed that these organizations could be used as effective transporters of material. This would account for part of the group identified herein. In addition, the welfare agencies might prove a valuable aid in reaching still other portions of the group.

RECOMMENDATIONS

The major recommendation emanating from this research is expansion of measurement. Given a fairly accurate instrument of measurement, it would be most beneficial to sample the entire San Joaquin Valley, State of California and eventually larger portions of the United States. Weather modification is a national (and even international) issue and deserves consideration from the point of view of the average citizen.

APPENDIX A

QUESTIONNAIRE

PERSONAL INFORMATION

1. Place of residence
   1. Urban
   2. Rural

2. Age
   1. 21-30 yrs.
   2. 31-40 yrs.
   3. 41-50 yrs.
   4. 50 yrs. and over

3. Length of residence in Fresno County
   1. 0-2 yrs.
   2. 2-4 yrs.
   3. 4-6 yrs.
   4. 6-8 yrs.
   5. 8-10 yrs.
   6. Over 10 yrs.

4. Occupation (if 2, indicate main occupation)
   1. Unemployed
   2. Agriculture (inc.laborer)
   3. Manufacturing (inc. lumber and wood products, metal, machinery, transportation equipment, food products, printing and publishing, etc.)
   4. Construction
   5. Transportation (inc.railroad and railway express service, communication, utilities, sanitary services, etc.)
   6. Wholesale-retail trade (inc. eating and drinking places, business and repair services, etc.)
   7. Miscellaneous (inc. educational and hospital services, public administration, professional services, private household, finance, real estate, insurance, other industries.)

5. Annual income (family total)
   1. Less than $5000
   2. $5000 - $9999
   3. $10,000 - $14,999
   4. $15,000 - $24,999
   5. $25,000 - or over

6. Educational background
   1. Less than high school
   2. High School
   3. Some college
   4. B.A. or B.S.
   5. B.A. or B.S. +
   6. M.A. or higher

7. Main area of study
   1. Business
   2. Education
   3. Social Sciences
   4. Science or Math
   5. Agriculture
   6. Liberal Arts
   7. Professional Studies
   8. Other _____ (specify)

8. Religious affiliation
   1. Protestant
   2. Catholic
   3. Jewish
   4. Agnostic
   5. Atheist
   6. Other _____
   7. None

9. In comparison to others of your religious affiliation, rate the degree of your participation

1	2	3	4	5	6	7	8
Very Much						Very Little	None

10. Political affiliation
    1. Democratic
    2. Republican
    3. Independent
    4. None

11. In comparison to others of your political affiliation, rate the degree of your participation in party or general political activities.

1	2	3	4	5	6	7	8
Very Much						Very Little	None

APPENDIX A - CONTINUED

WEATHER MODIFICATIONS SURVEY

(As you complete this questionnaire, keep in mind our definition of weather modification: Seeding clouds to increase the amount of rainfall and thus, the water supply.)

12. Rate how much weather affects your life in terms of income

1	2	3	4	5	6	7
Very Little						Very Much

13. Rate the importance of weather in your leisure time activities

1	2	3	4	5	6	7
Very Little						Very Much

How do you feel when it is:

14. Sunny

1	2	3	4	5	6	7
Good						Bad

15. Foggy

1	2	3	4	5	6	7
Good						Bad

16. Windy

1	2	3	4	5	6	7
Good						Bad

17 Cloudy

1	2	3	4	5	6	7
Good						Bad

18. Rainy

1	2	3	4	5	6	7
Good						Bad

19. Are you aware that weather modification is going on in the Valley?
    1. Yes
    2. No

20. How long do you think weather modification has been going on in the Valley? (In years)

21. What effect do you think weather modification has had upon the water supply in the Sierra Nevada Mountains?
    1. Decreased by more than 10%
    2. Decreased 0 - 10%
    3. No change
    4. Increased 0 - 10%
    5. Increased more than 10%
    6. No knowledge of the effect

22. What effect does the chemical used to seed clouds have on plant or animal life?

1	2	3	4	5	6	7	8
Very Beneficial					Very Harmful		No Knowledge

23. What qualifications should a person have who attempts to modify the weather?
    1. Meteorology
    2. Engineering
    3. None
    4. Astrology
    5. Physics
    6. No opinion

24. Who does the water in the clouds belong to?
    1. The U S. Government
    2. United Nations
    3. Individual states
    4. Local communities
    5. Owner of property over which clouds pass
    6. A supreme being
    7. No one

25. What financial responsibility should be required of a modifier?
    1. Post bond to cover property damage
    2. Carry insurance to cover property damage
    3. None

26. Who should have regulatory control over weather modification (i.e., determining how often and how extensive operations should be)?
    1. Federal government
    2. State government
    3. Local government
    4. Individual property owners
    5. Public utilities companies

27. Do you approve of weather modification?

1	2	3	4	5	6	7
Strongly in favor						Strongly opposed

28. What is the relationship between weather modification and Divine laws of the universe?
    1. Utilizes natural laws
    2. Defies natural laws
    3. Has no effect

29. My religious convictions:
    1. Cause me to be opposed to any weather modification activity
    2. Have no effect upon my attitude toward weather modification

30. Who has the responsibility for any damages occurring by weather modification?
    1. The weather modifier
    2. The person who hires the modifier

31. Should any public notification be required of weather modification attempts?
    1. Yes, always
    2. Yes, only when it may effect populated areas
    3. No

How serious do you feel the following issues are in relation to weather modification?

32. Government regulation of activities

1	2	3	4	5	6	7	8
Very Serious					Not Serious		No Knowledge

33. Financing of weather modification (e.g.,tax, individual, etc.)

1	2	3	4	5	6	7	8
Very Serious					Not Serious		No Knowledge

34. Moral issues

1	2	3	4	5	6	7	8
Very Serious					Not Serious		No Knowledge

35. Pollution caused by chemicals used in modification activities

1	2	3	4	5	6	7	8
Very Serious					Not Serious		No Knowledge

36. Problems involving international politics

1	2	3	4	5	6	7	8
Very Serious					Not Serious		No Knowledge

37. Modification as a potential military weapon (similar to nuclear power)

1	2	3	4	5	6	7	8
Very Serious					Not Serious		No Knowledge

38. Development of appropriate laws to deal with related problems

1	2	3	4	5	6	7	8
Very Serious					Not Serious		No Knowledge

Rate the importance of the following in your personal life:

39. Religion

1	2	3	4	5	6	7
Very Important						Least Important

40. Conservation

1	2	3	4	5	6	7
Very Important						Least Important

41. Outdoor sports

1	2	3	4	5	6	7
Very Important						Least Important

42. Travel

1	2	3	4	5	6	7
Very Important						Least Important

43. Politics

1	2	3	4	5	6	7
Very Important						Least Important

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(2) Henderson, T. J., "A Ten Year Non-randomized Cloud Seeding Project on the Kings River in California." Journal of Applied Meteorology, Vol. 5, October 1966.

(3) Williams, Merlin C., "Atmospheric Water Resources Research Annual Report No. 1, Summary." under Bureau of Reclamation Contract No. 14-06-D-6592, September 1, 1969.

(4) Hays, William L., "Statistics for Psychologists." Holt, Rinehart and Winston, New York, 1963. p 493.

on the features of legislation that are considered to be desirable to accomplish the objectives stated above.

Although the elements of a model law described below are directed primarily at state legislation, the same elements would be applicable in Federal legislation.

1. PURPOSE - It is recognized that economic benefits can be derived from weather modification which will benefit the people of the State. Operations, research, experimentation, and development in the field of weather modification shall therefore be encouraged. In order to minimize possible adverse effects, weather modification activities shall be carried out with proper safeguards, and accurate information concerning such activities shall be made available for purposes of regulation. Weather modification is declared not to be an ultra-hazardous activity, and the consequence of materials and substances being disseminated into the atmosphere pursuant to an authorized project shall not give rise to any cause of action by any party based upon the contention or concept that such use of the atmosphere constitutes trespass or involves an actionable nuisance.

2. DEFINITION - Activities known as "weather modification" which are covered by the statute shall be defined. The definition should not be so specific that new methods or objectives of weather modification are excluded from coverage. We suggest the following definition of weather modification: Changes in the composition, behavior, or dynamics of the atmosphere which are artificially and intentionally induced.

3. BOARD - A Board shall be established, consisting of members chosen mainly from private life who represent interests concerned with water resources as they affect agriculture and industry. In addition, there shall be at least one member possessing technical competence in meteorology or in a related scientific field. No member of the Board may be at the time of appointment an employee of a person or corporation engaged in commercial weather modification, a corporate officer or director of a weather modification corporation, a self-employed weather modifier, a salaried employee of a government weather modification activity, or anyone having a substantial financial interest in weather modification operations or research. Any Board member who acquires a direct financial interest in weather modification after his appointment as a Board member shall be ineligible for continued membership on the Board.

The manner in which the Board members shall be chosen, together with the term of their service, shall be defined.

4. LICENSE - The Board shall be empowered to issue licenses to modify the weather. No person or agency may modify weather without a license.

5. FINANCIAL RESPONSIBILITY - The Board shall require the applicant to submit proof of financial responsibility before a license is issued, in

order to give reasonable assurance of protection to the public in the event it should be established that damages were caused to third parties as a result of negligence in carrying out the project.

6. QUALIFICATIONS - In issuing licenses, the Board shall establish qualifications for licensees. These qualifications shall be in keeping with the qualifications currently recognized by professional and scientific associations concerned with the field of meteorology and/or weather modification.

7. FEE - The Board shall establish a license fee within statuatory limitations. The term of the license shall be for 12 consecutive months, and may coincide with the principal precipitation season or water year.

8. LICENSE RENEWAL - The Board shall establish conditions for the renewal of a license. The Board may revoke a license should the licensee cease to meet license qualifications, or should the licensee violate the statute. Revocation may occur only after a hearing before the Board.

9. PROJECT - "Project" shall be defined as the performance of weather modification activities limited to a single geographical area, over a continuing period of one year or less.

10. PERMIT - The Board shall be empowered to issue permits regulating permissible areas and times of operation for a project. A separate permit must be obtained for each project. One licensee may not transfer a permit to another licensee. The Board shall issue a permit only after establishing that the project will provide economic benefits, or that it will enhance scientific knowledge. The Board may issue only one active permit at a time for activities in a given geographic area, so that no two licensees have overlapping project areas.

11. OPERATIONAL PLAN - A complete operational plan for each proposed project shall be prepared by a licensee, to include a specific statement of objectives, a map of the proposed operating area, and such other detailed information as may be required to describe the operation and its proposed method of evaluation. This operational plan shall be placed on file with the Board and with such other agent(s) as the Board may require. After the licensee has secured a permit, and before beginning operations, the licensee shall publish a notice of intent to modify weather in the principal newspapers of the counties to be affected by the weather modification program. The published notice shall indicate the general area, expected duration, and intended effect, and that complete details are available on request from the licensee or the Board or from the other agent(s) specified by the Board. The notice shall run for two consecutive weeks and proof of publication shall be furnished to the Board by the licensee.

12. EMERGENCY - A project permit may be granted by the Board without prior publication of notice by the licensee in cases of evident fire, fog, or drought emergency. In such cases, publication of notice shall be performed as soon as possible.

13. OPERATIONS LOGS - The Board shall establish requirements for the keeping of generator operations logs and their reporting for the intention of records.

14. INJUNCTION - The Board shall have power to enjoin use of a project permit pending hearing providing that in issuing such an injunction it shall provide for indemnification of the party against whom the injunction is issued, indemnifying him for any and all losses resulting from the issuance of the injunction.

15. REVOCATION OF LICENSE - Failure to file legally required reports, or late filings, may be cause for revocation of license. The Board shall establish procedures for revocation under this provision.

16. RECORDS AVAILABLE - Records of weather modification projects which are in the possession of the Board shall be available for public inspection.

17. ANNUAL REPORT - A summary of all current weather modification projects in the State, together with a general evaluation of them should be prepared annually for the Board by a qualified individual or institution appointed for this purpose.

18. BOARD FUNCTIONS - In order to perform functions necessary to carry out this statute, the Board may:

(a) establish minimum standards of weather modification activities;

(b) conduct studies, investigations, and hearings;

(c) establish advisory committees;

(d) represent the State, with the consent of the Governor, in all matters pertaining to interstate, Federal-State, or other intergovernmental cooperation in weather modification activities.

19. REGULATORY AGENCY - The Board should have the powers of a regulatory agency to hold hearings, hear complaints, and make determination of fact.

20. FINANCING - The financing of the Board shall be provided for from State funds.

21. BOARD ACTIVITIES - The Board shall not engage in weather modification activities, either directly or by contract.

22. PENALTIES - Penalties for violating this statute shall be defined.

23. LIABILITY - Nothing in the statute shall be construed as acceptance by the State of liability for weather modification activities.